GREAT DESIGNS IN STEEL

BOUNDARY CONDITION INFLUENCE ON EDGE FRACTURE OF A 980GEN3 AHSS

Advaith Narayanan

University of Waterloo

(Presenting for Auto/Steel Partnership)

A/S P

PROJECT TEAM

University of Waterloo

Advaith Narayanan (PhD Candidate)

Ryan George (Research Associate)

Cliff Butcher (Associate Professor)

Auto/Steel Partnership: Steel Testing and Harmonization Team

Jonathan Smith (Project Manager)

Eric McCarty (Senior Project Manager)

Technical Leads

Jugraj Singh, Stellantis

Dean Kanelos, Nucor Corporation

OUTLINE

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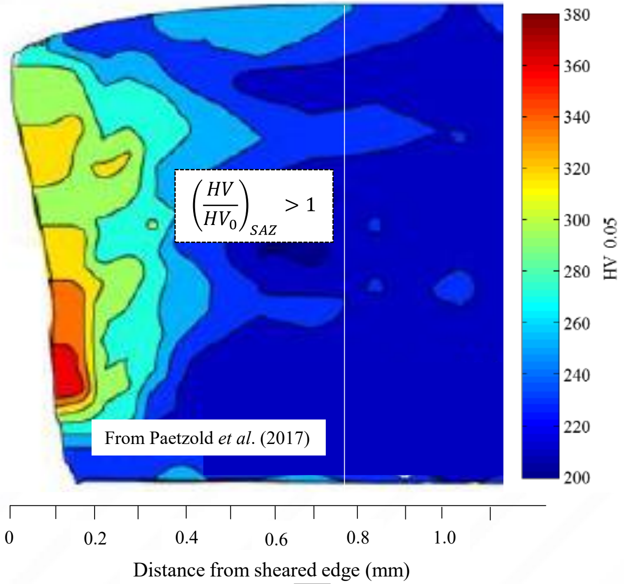
- Introduction & Challenges with Sheared Edge Fracture Characterization
- Objectives
- In-Plane Bend Test: Design & Experiments
- Hole Tension Tests
- Conical and Flat Punch Hole Expansion
- Edge Fracture Tension Tests
- Comparison of Fracture Strains for 980GEN3 Steel
- Summary & Future Work

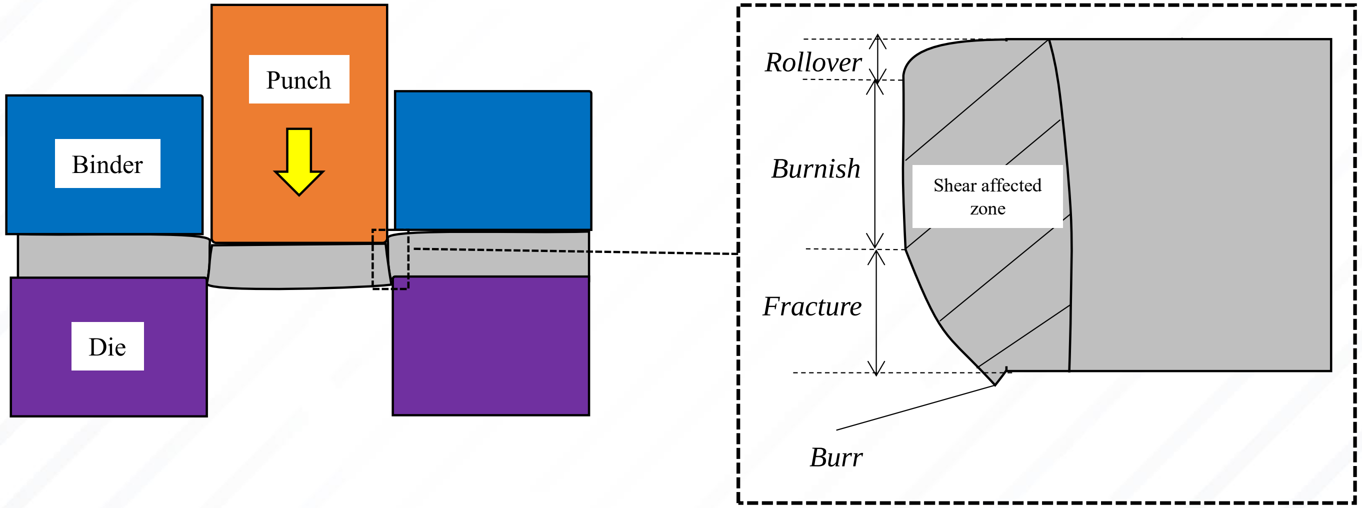
FAILURE DURING SHEARED EDGE STRETCHING

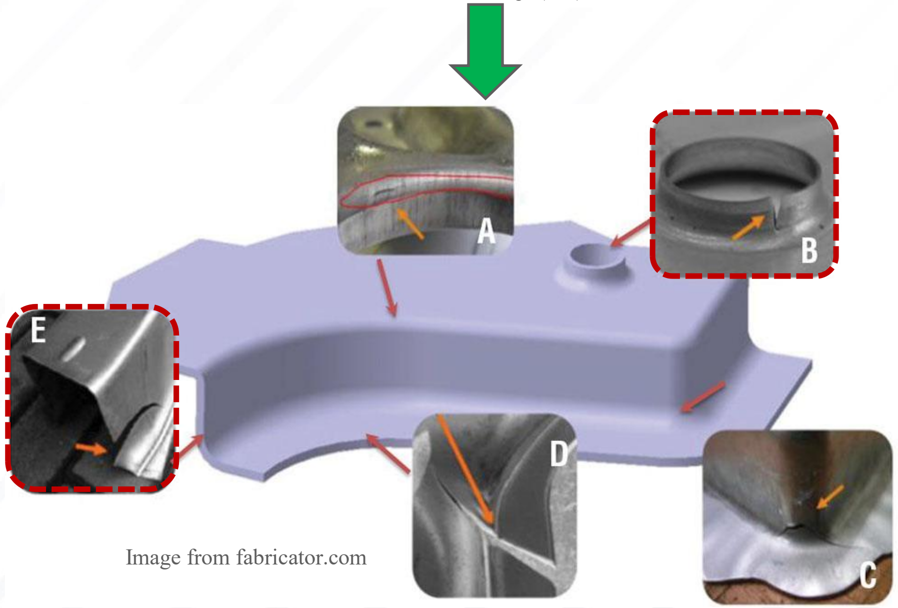
Four cut edge zones are formed after shear cutting.

Extensive strain hardening in the shear affected zone (SAZ).

The SAZ can promote edge splitting during subsequent forming.







Paetzold, I., Dittmann, F., Feistle, M., Golle, R., Haefele, P., Hoffmann, H. and Volk, W., 2017, September. Influence of shear cutting parameters on the fatigue behavior of a dual-phase steel. In *Journal of physics: conference series* (Vol. 896, No. 1, p. 012107). IOP Publishing.

CONICAL HOLE EXPANSION (HX) TO EVALUATE EDGE FRACTURE LIMITS

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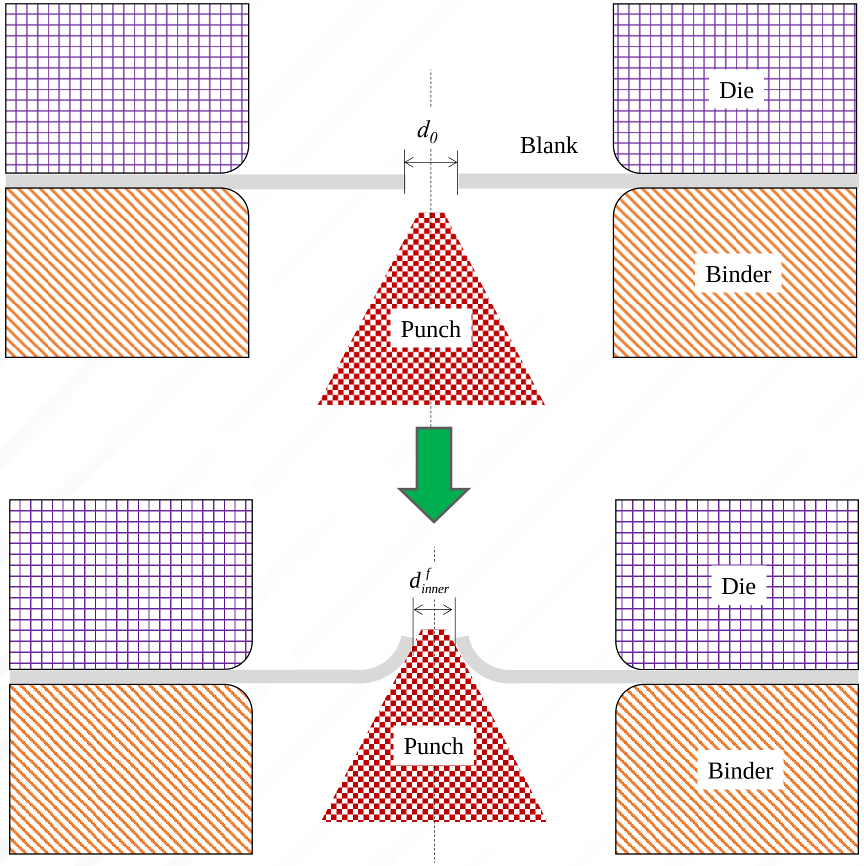
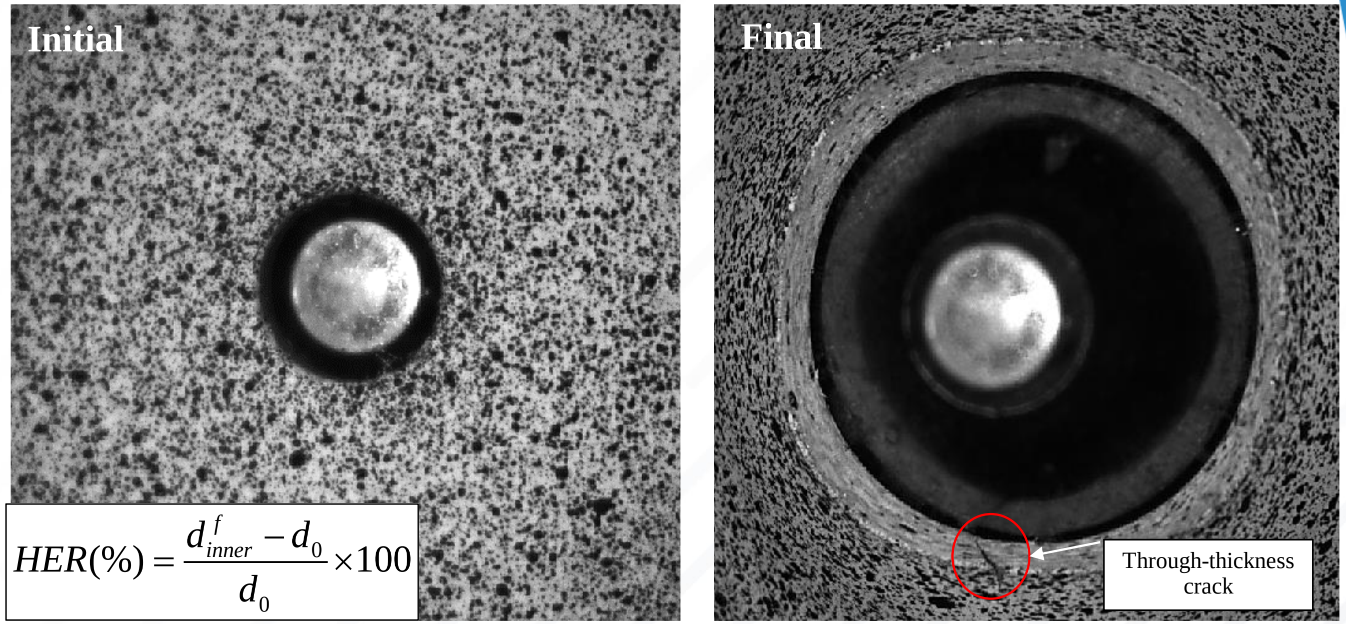
Conical HX mimics hole extrusion. Hole expansion ratio (HER) evaluated at cracking.

The test does not emulate failure under in-plane bending or stretching modes!

Need a failure strain value from the test to input into sheared edge finite-element (FE) models.





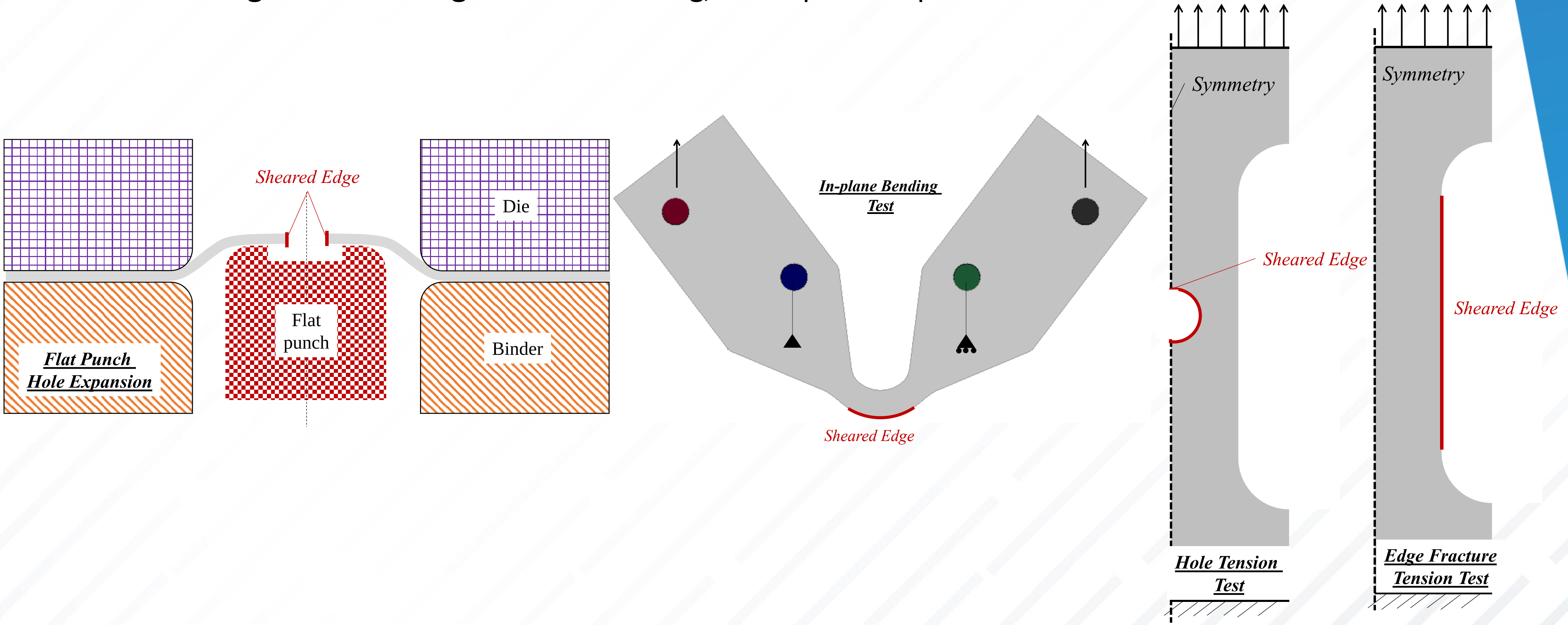
$$HER(\%) = \frac{d^f_{inner} - d_0}{d_0} \times 100$$

OTHER TESTS TO CHARACTERIZE EDGE FRACTURE

In-plane stretching ➔ Flat punch HX, hole tension, edge fracture tension

In-plane bending ➔ double bending test, in-plane bending test

Combined bending and stretching ➔ collar forming, hemispherical punch HX



WHAT IS THE BEST EDGE FRACTURE TEST?

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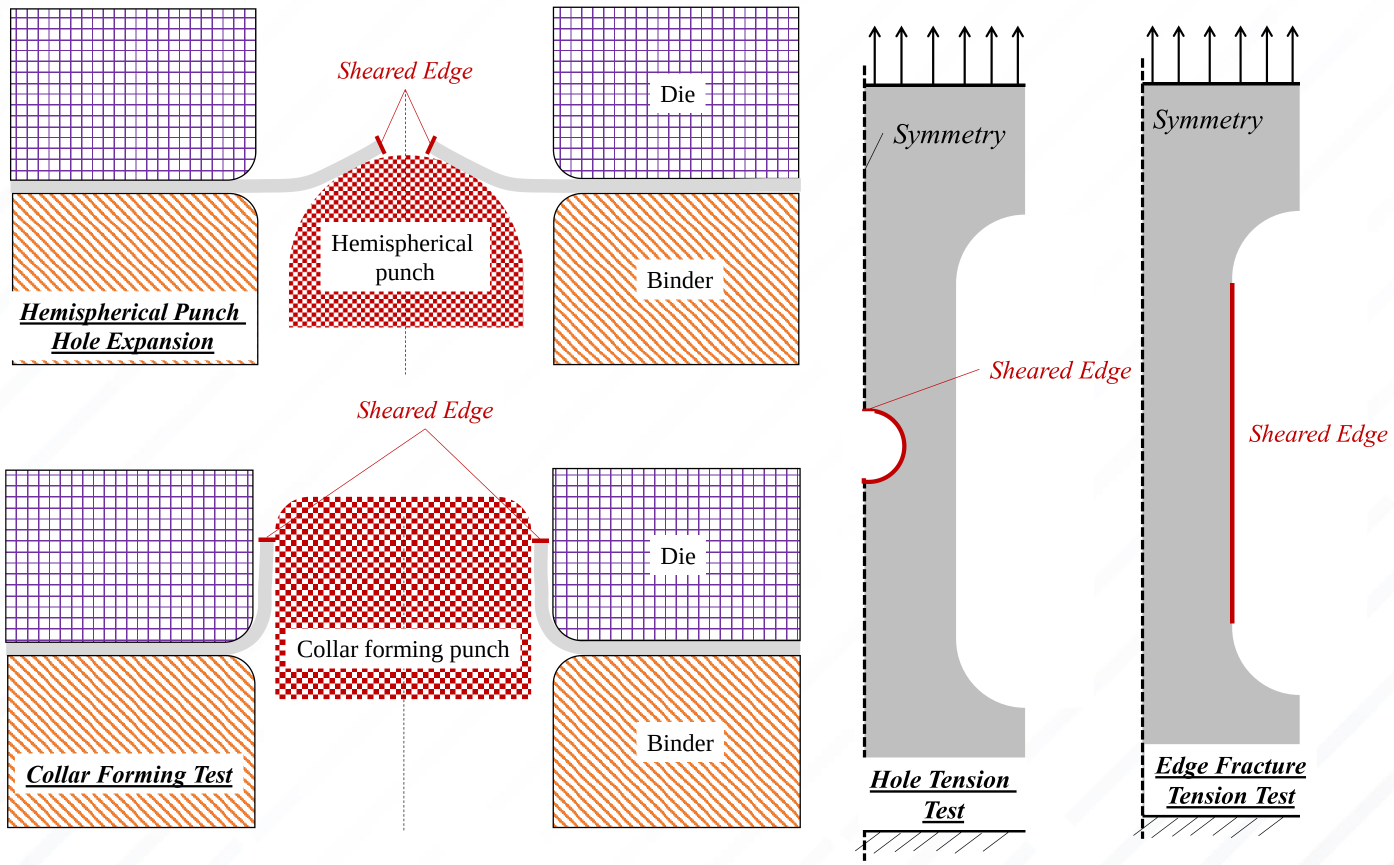
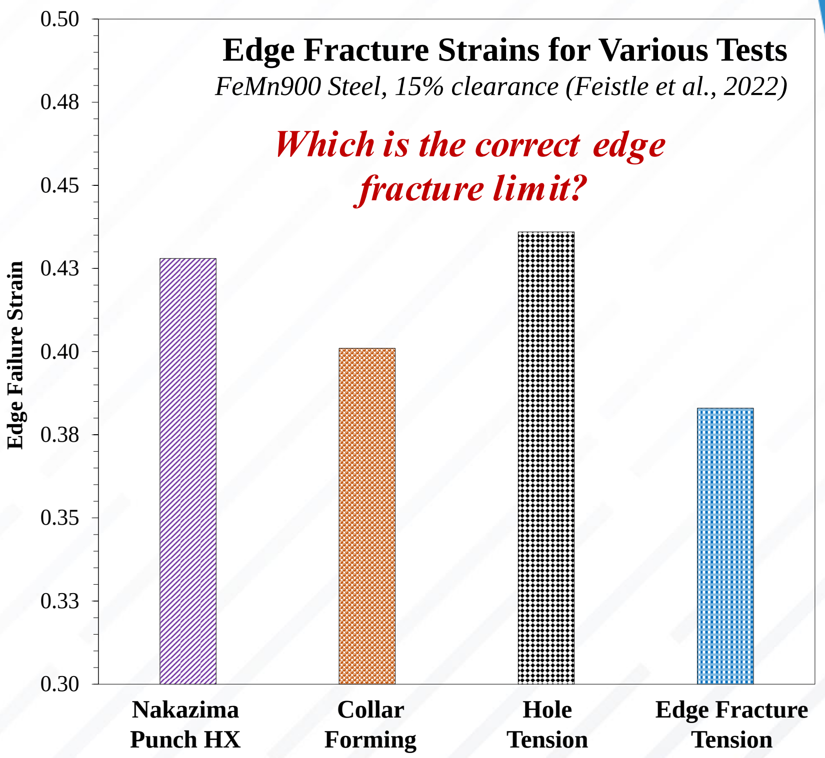
The sheared or machined edge is under uniaxial tension as it is a free surface.

<u>However, the fracture strains among tests can differ depending upon the material!</u>





Feistle, M., Golle, R. and Volk, W., 2022. Edge crack test methods for AHSS steel grades: A review and comparisons. *Journal of Materials Processing Technology*, *302*, p.117488.

BOUNDARY CONDITIONS DURING EDGE STRETCHING

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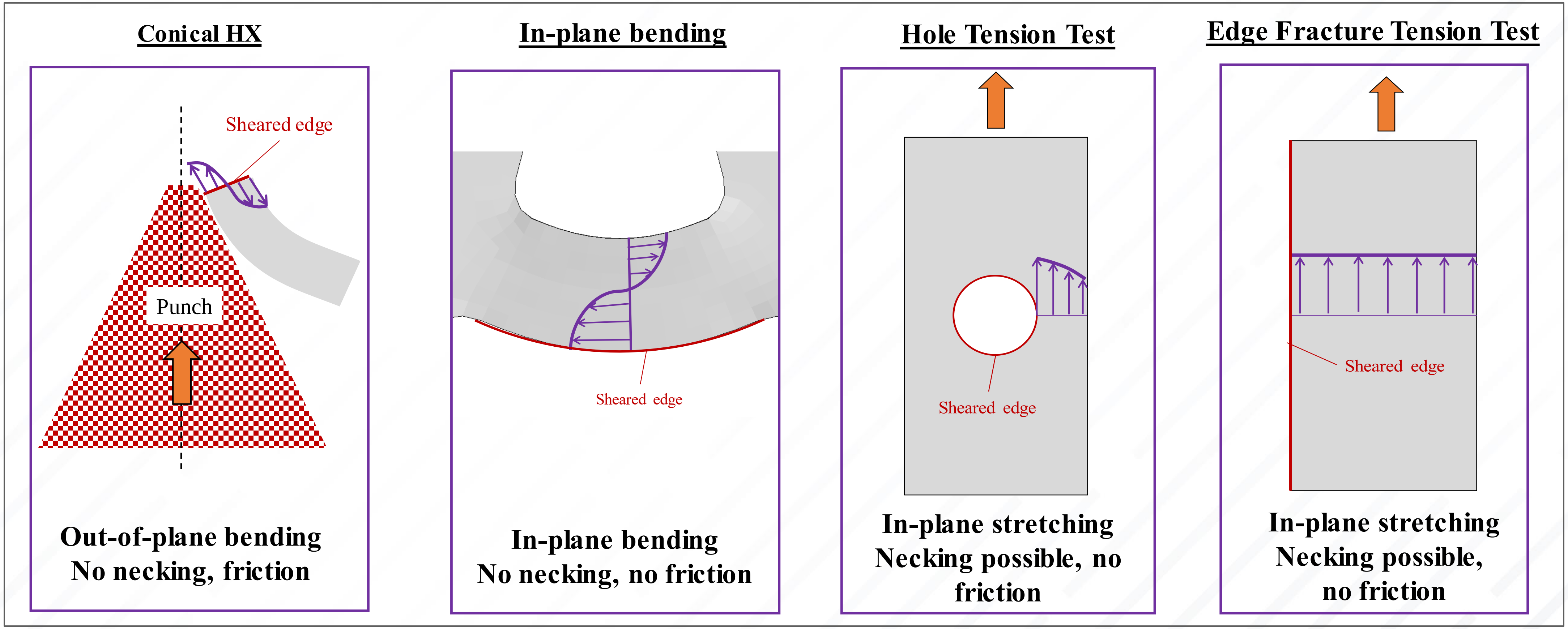
Differences in stress and strain gradients surround the edge can alter fracture strain.



OBJECTIVES

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Assess boundary condition effect on edge fracture limits of a 980GEN3 steel.

➔ Consider both CNC and sheared edge conditions.

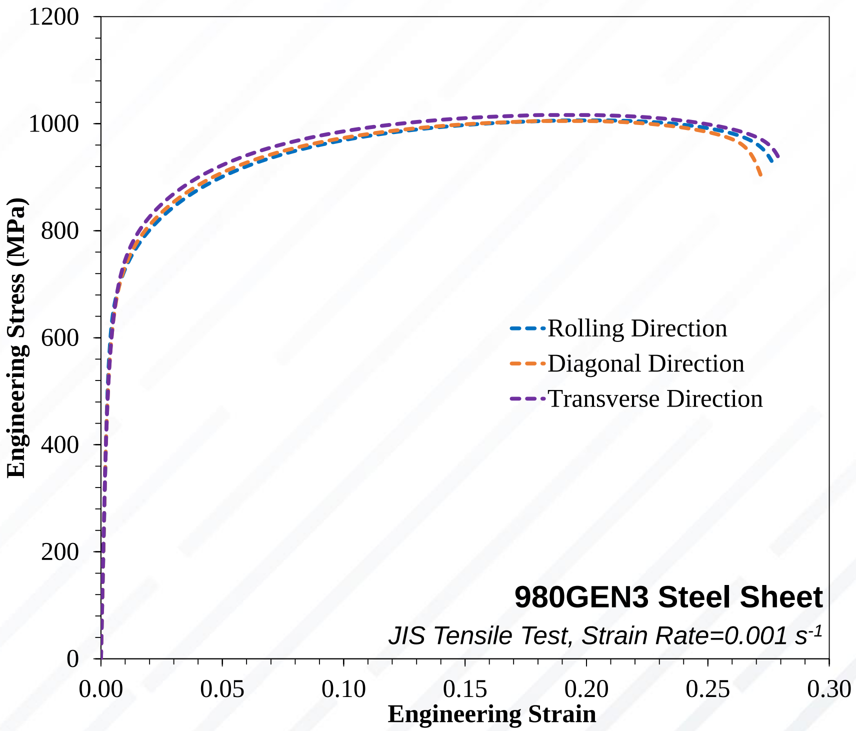
➔ In-plane bending, hole tension, conical and flat punch HX, and edge fracture tension tests.

➔ *All DIC-based tests were processed using a virtual strain gage length (VSG_m) of ~1.0 mm.*

VSG_m(mm)= [(Filter-1)×Step (pixel) + Subset (pixel)]×Image Scale (mm/pixel)=1.0 mm

Tensile Property	Rolling Direction	Diagonal Direction	Transverse Direction
0.2% Yield Strength (MPa)	654 ± 2	633 ± 2	624 ± 5
Ultimate Tensile Strength (MPa)	1006 ± 2	1010 ± 2	1012 ± 6
Uniform Elongation UE (%)	19.5 ± 0.1	19.0 ± 0.1	18.7 ± 0.1
Total Elongation (%)	27.7 ± 0.1	27.3 ± 0.1	28.0 ± 0.1
Avg. R-value: Linear Fit	0.85 ± 0.02	0.95 ± 0.02	1.05 ± 0.04

<ins>All edge fracture characterization tests were conducted with principal stretching along the TD in the burr-up configuration.</ins>



SHEAR CUTTING PARAMETERS (CLOSED-LINE)

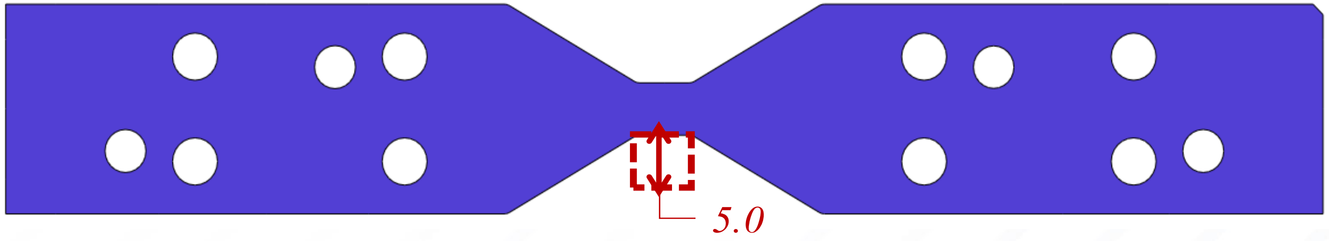
Cutting Clearance: 12% of sheet thickness

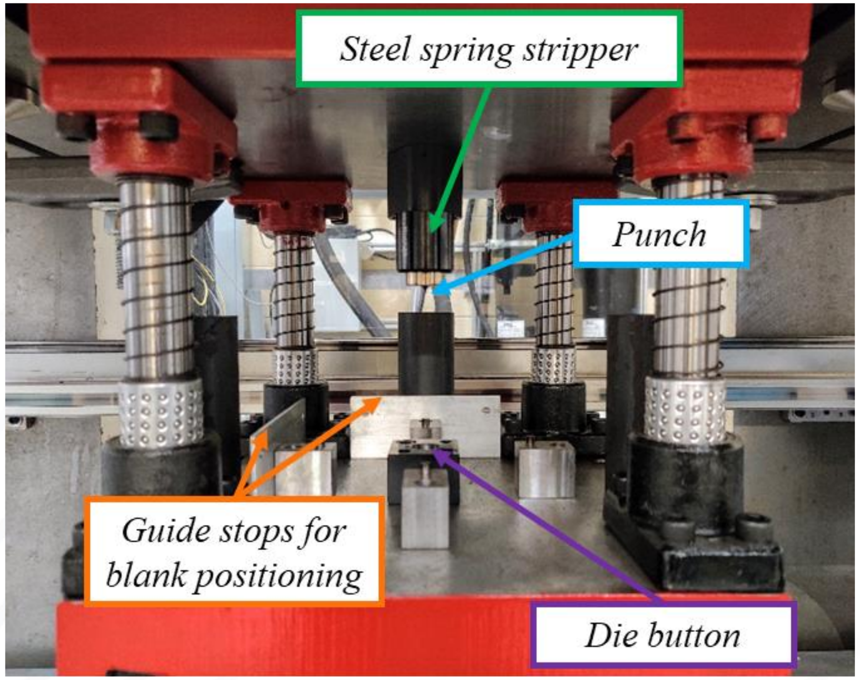
Cutting Speed: 50 mm/s

Cutting Shape: Circle or Square

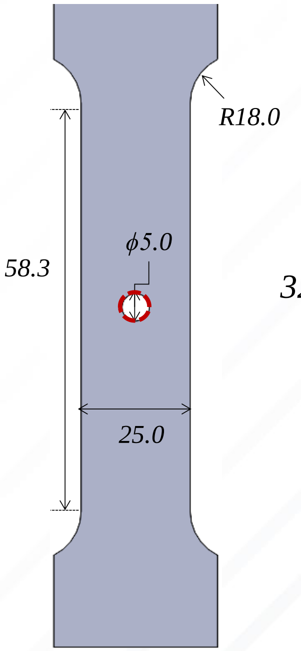
Hole Size/Diameter: 5.0 mm

In-Plane Bending

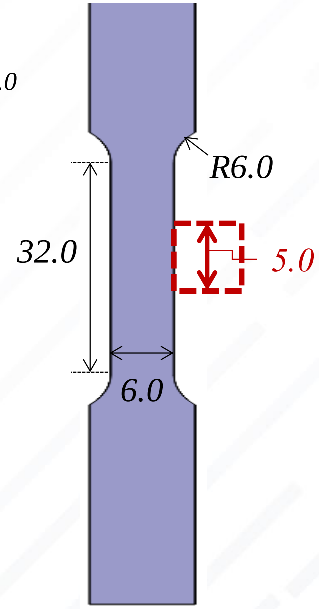




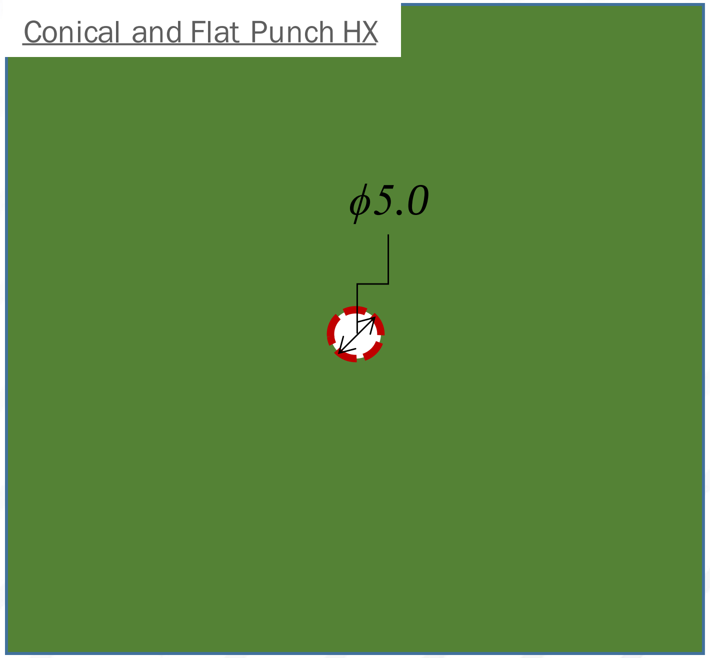
Hole Tension



Edge Fracture Tension



Conical and Flat Punch HX



Red circles and squares indicate sheared edge outline

DESIGN OF THE IN-PLANE BEND TEST FIXTURE

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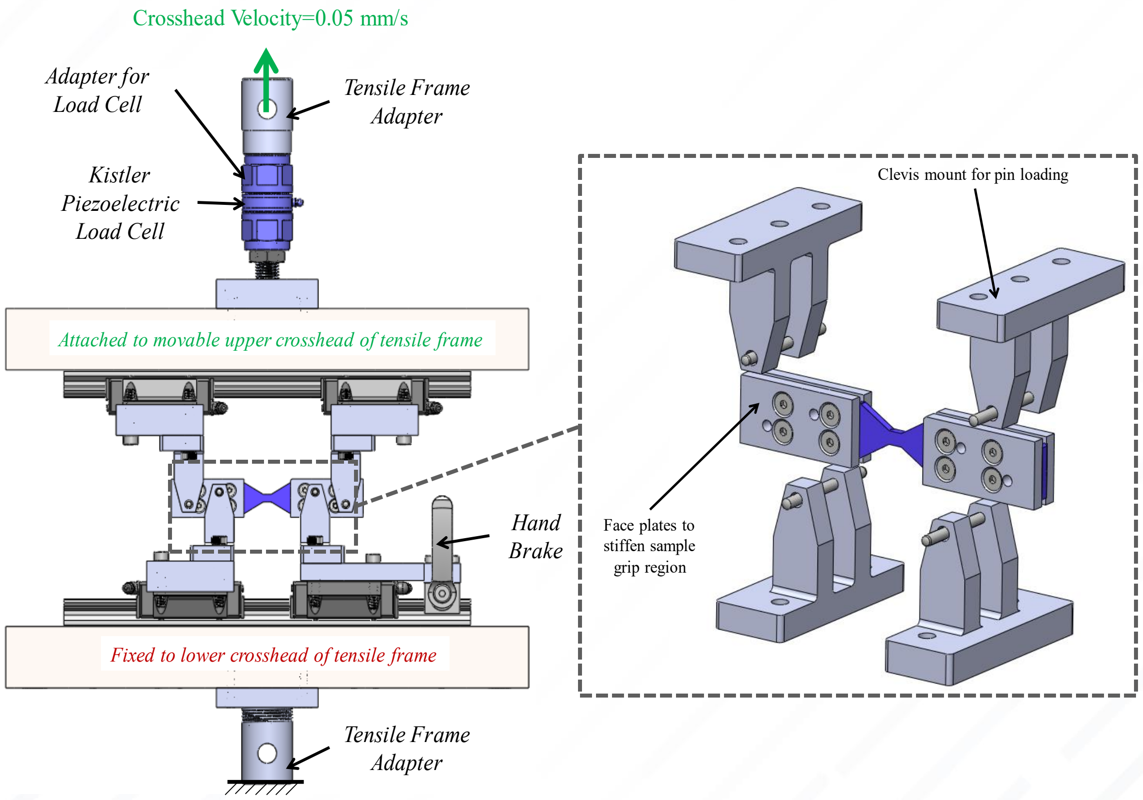
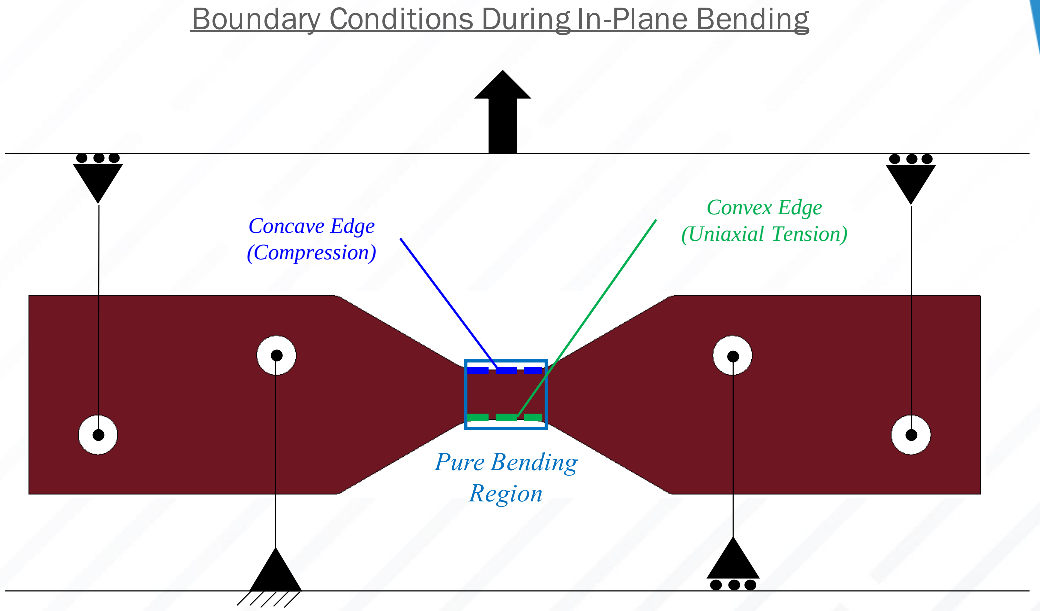
A 4-point bend test was proposed by UTwente. Design modified for characterization to ~70% strain.

Bending occurs in the plane of sheet metal and not through-thickness like in V-bending.

No contact between blank and tools. PTFE spray applied as lubricant to ensure free sample rotation.





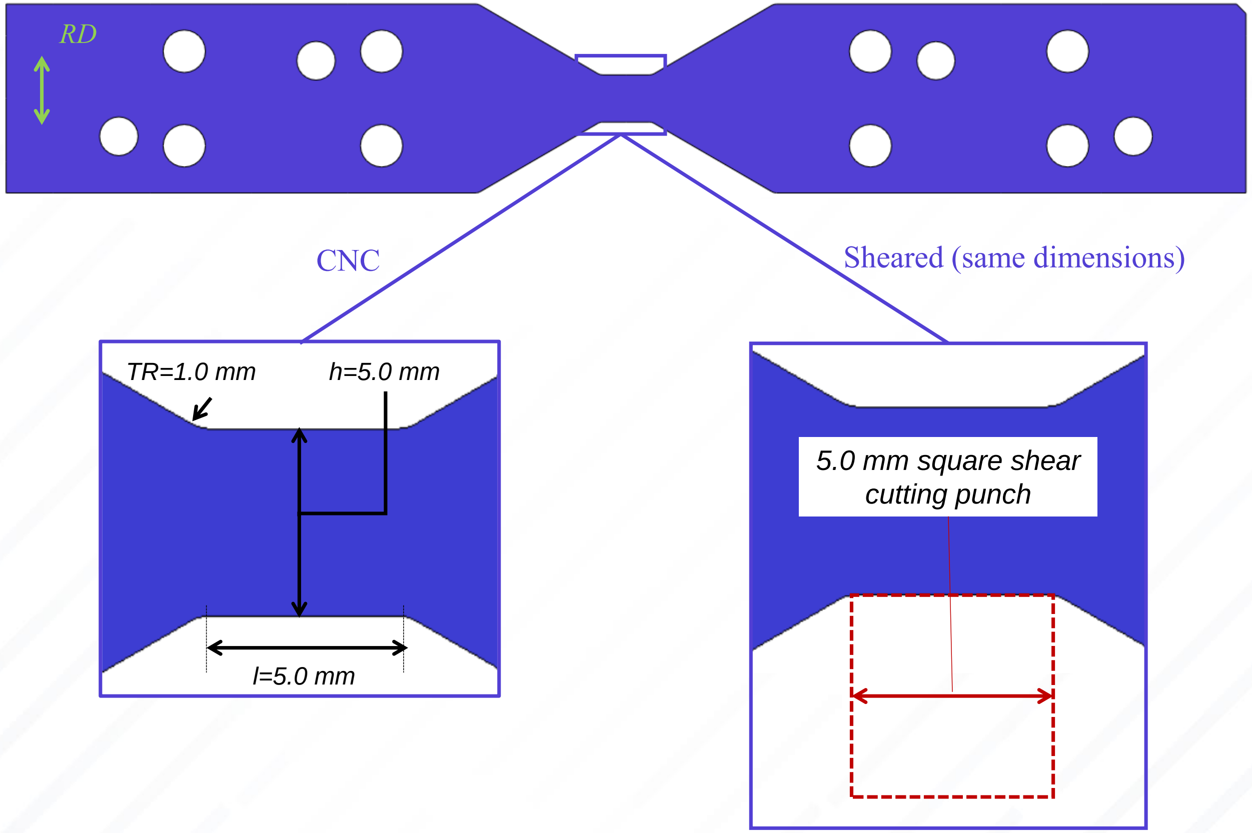
Naseem, S., Perdahcıoğlu, E.S., Geijselaers, H.J.M. and van den Boogaard, A.H., 2020. A new in-plane bending test to determine flow curves for materials with low uniform elongation. *Experimental mechanics*, *60*, pp.1225-1238.

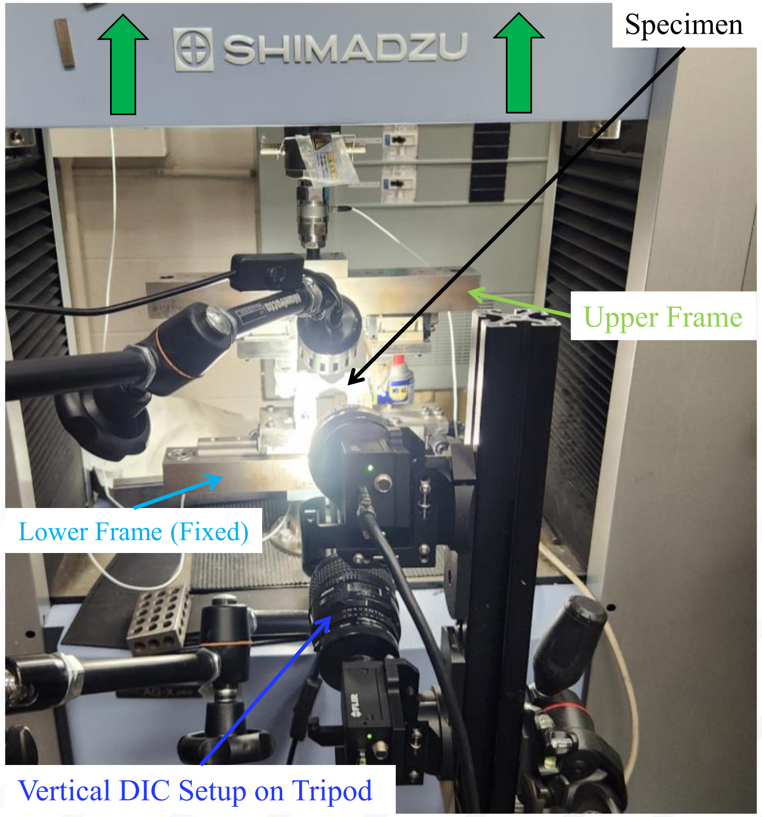
IN-PLANE BEND TEST GEOMETRY & SETUP

Gage section geometry chosen based on parametric study conducted using FEA.

Larger gage height (h) and length (l) promote higher strain gradient and edge deformation.

Vertical DIC setup for better focus during specimen bending.





Narayanan, A. and Butcher, C., 2023. Design of a Test Geometry to Characterize Sheared Edge Fracture in a Uniaxial Bending Mode (No. 2023-01-0730). SAE Technical Paper.

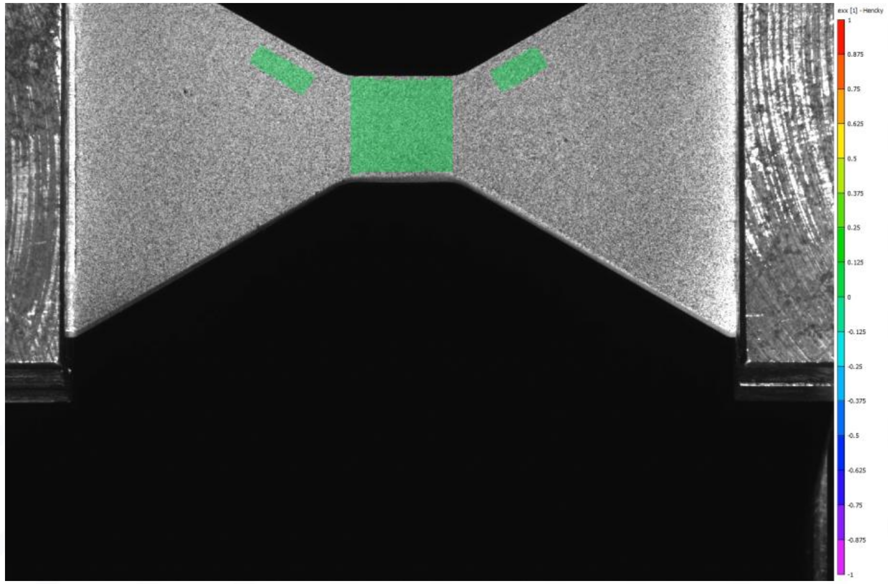
DIC STRAIN EVOLUTION DURING IN-PLANE BENDING

Crack initiates on the convex side for both sheared and CNC machined edges.

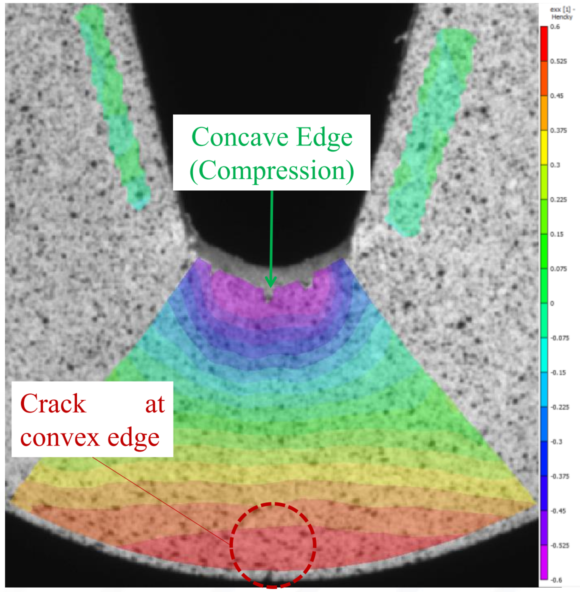
In-plane bend test activates uniaxial and compressive deformation in a single test.

The unelongated layer can be tracked using DIC to potentially evaluate kinematic hardening models.

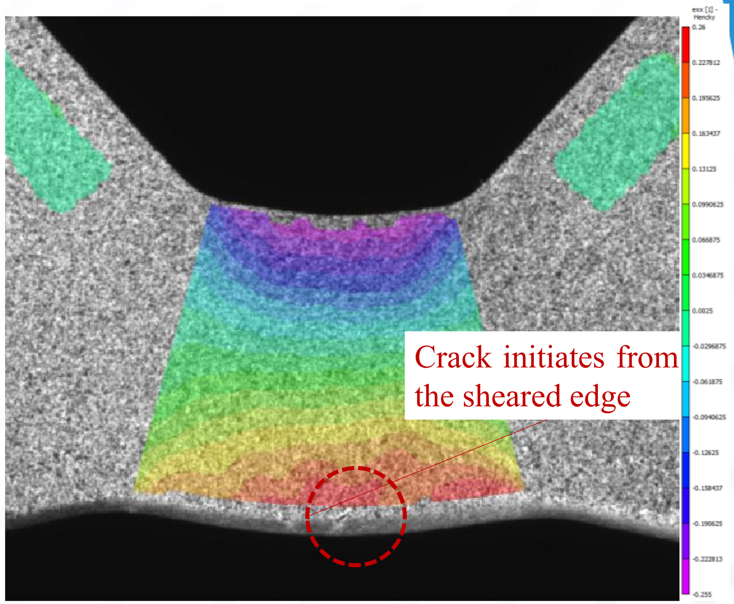
980GEN3 DIC Strain Evolution: Sheared Edge (Burr Up)



ε_{xx} Contour: CNC Machined



ε_{xx} Contour: Sheared

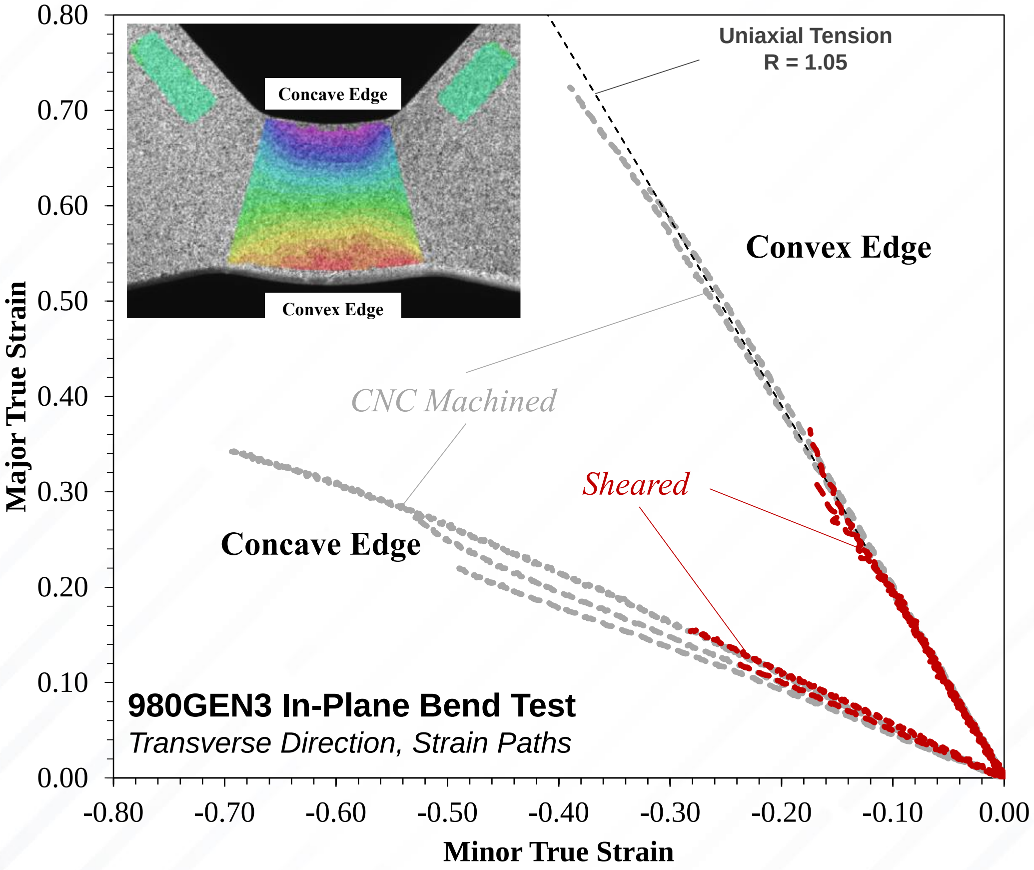


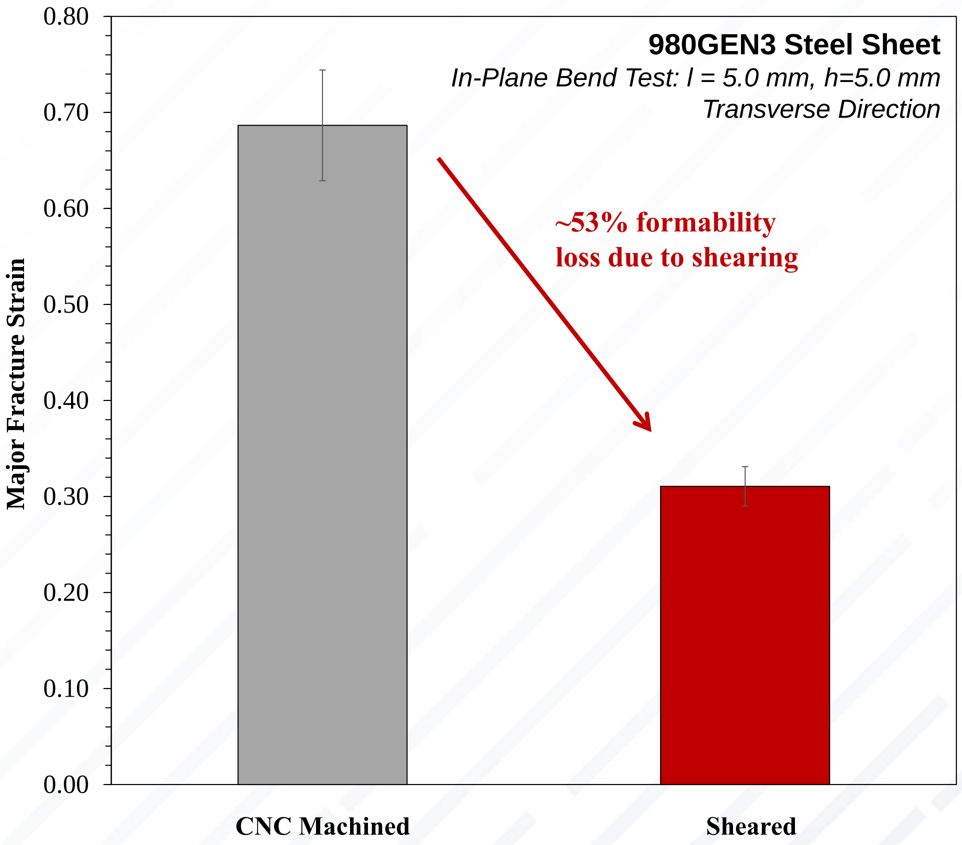
IN-PLANE BENDING: SHEARED VC CNC STRAINS

Linear strain paths until fracture. Necking suppressed due to stress state and strain gradient.

Can investigate fracture anisotropy using the in-plane bend test by modifying machining direction.

Sheared edge strains lower by ~53% relative to CNC machined condition.





IN-PLANE BENDING: AMENABILITY TO FE MODELLING

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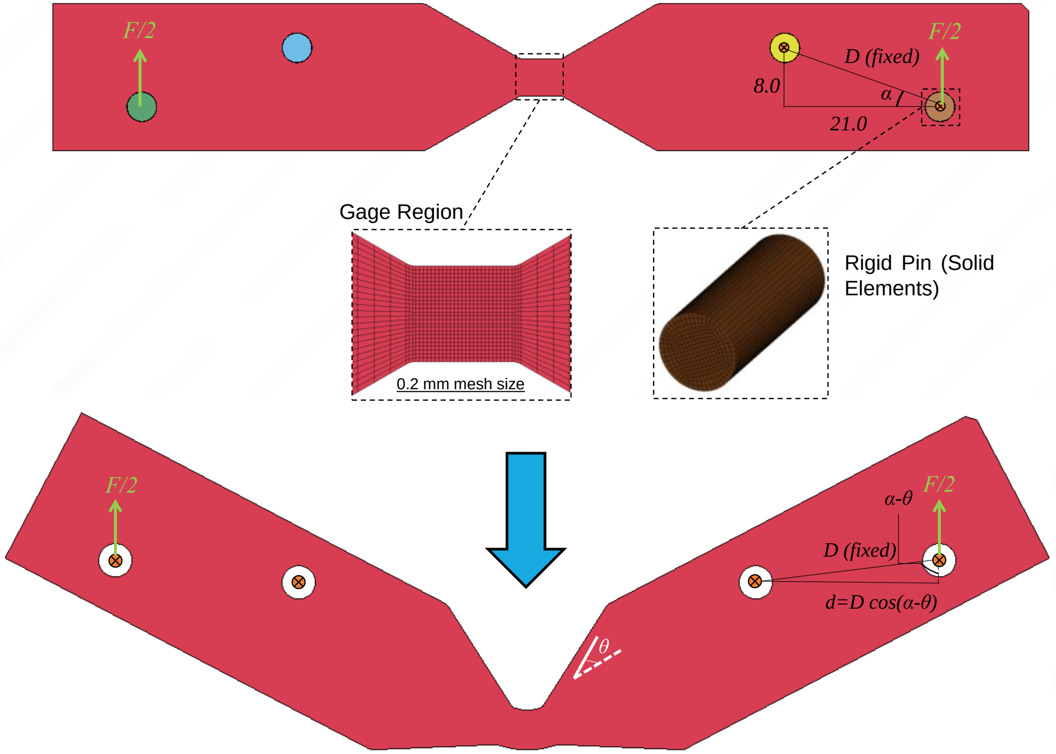
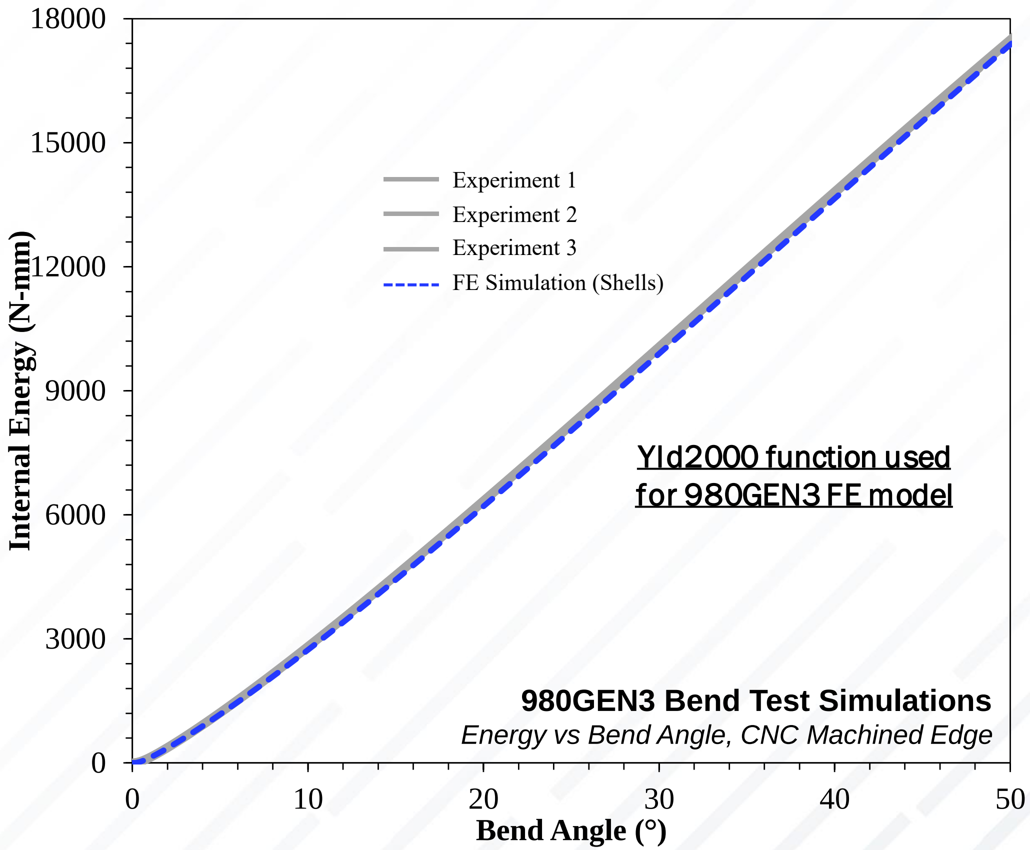
In-plane bend tests can be simulated using shell elements with plane stress anisotropic yield function.

➔ Can compare local edge strains, bending moment, and energy versus experiments.

➔ ***Next steps: adapt to FE modelling of sheared edges, assess element lengthscale effect.***



$$M=\frac{F}{2}\times D\cos(\alpha-\theta);\ E=2\int_0^{\theta}Md\theta$$



HOLE TENSION: FAILURE LOCATION ASSESSMENT

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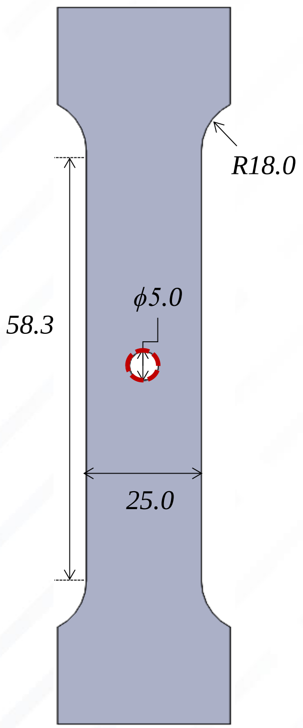
Geometry in accordance with optimal gage width to hole diameter ratio obtained by Roth and Mohr (2016).

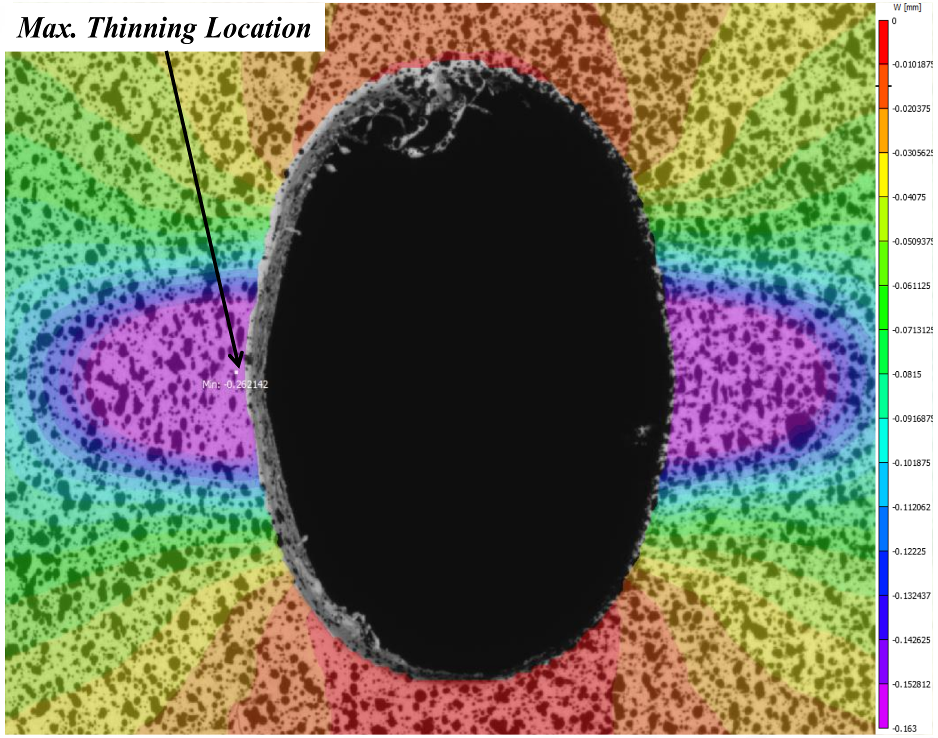
Failure behind the edge is possible in a machined hole tension test depending upon the material.

For 980GEN3, maximum thinning and fracture occurs at or very close to the hole edge.

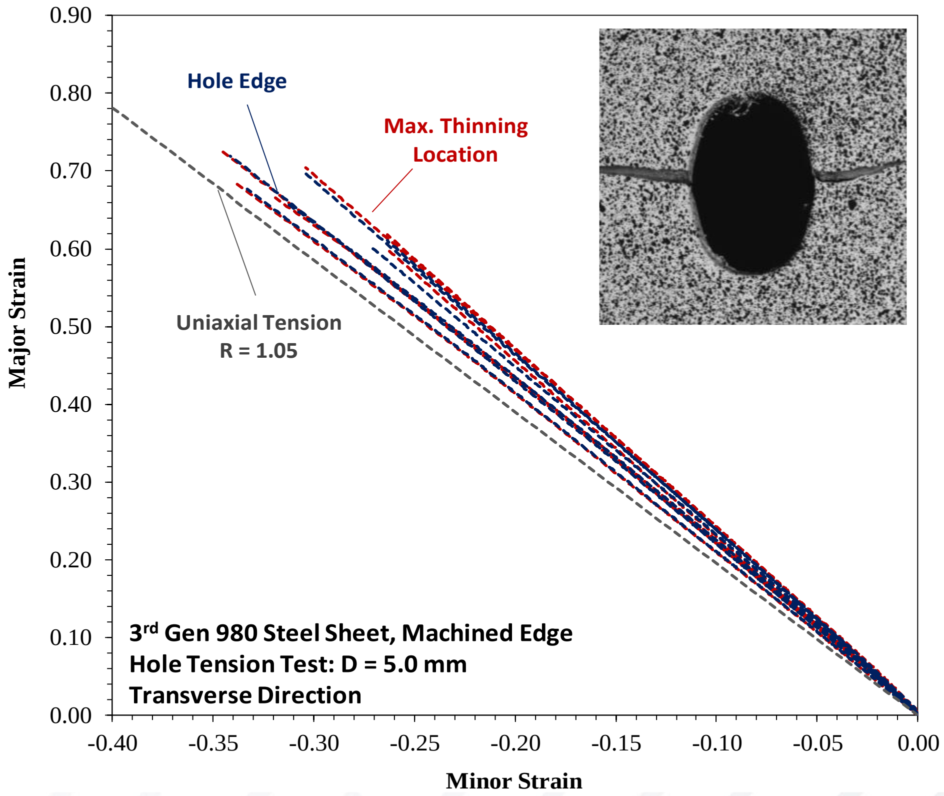
Hole Tension Geometry



W-Displacement – CNC Machined Edge



Strain Paths during Hole Tension



Roth, C.C. and Mohr, D., 2016. Ductile fracture experiments with locally proportional loading histories. *International Journal of Plasticity*, *79*, pp.328-354.

HOLE TENSION TESTS: CNC VS SHEARED EDGE

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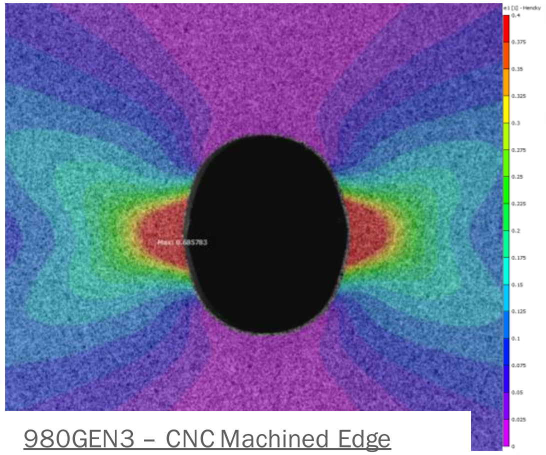
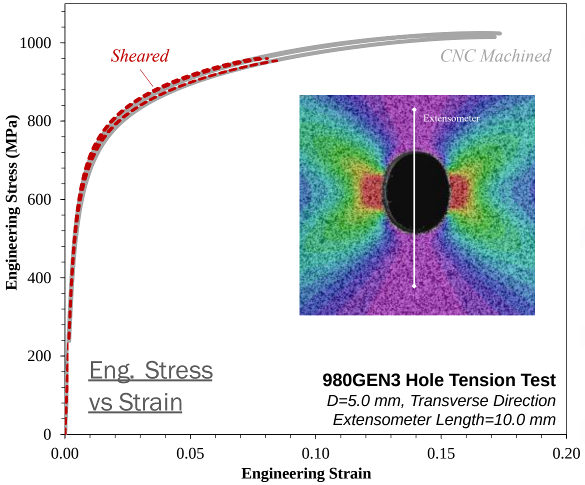
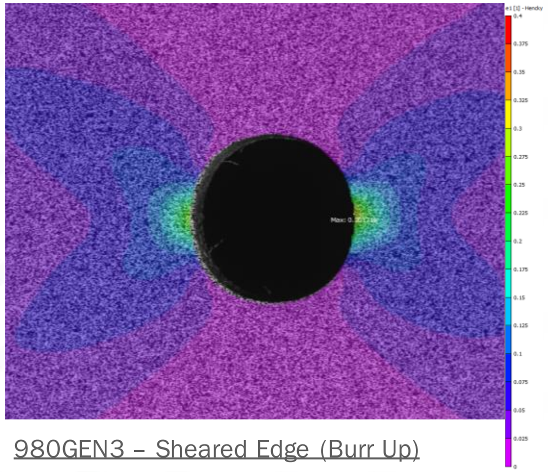
Sheared edge promotes premature failure at hole boundary due to SAZ strain hardening.

Fracture strain for a sheared edge is ~55% lower than the baseline CNC hole.

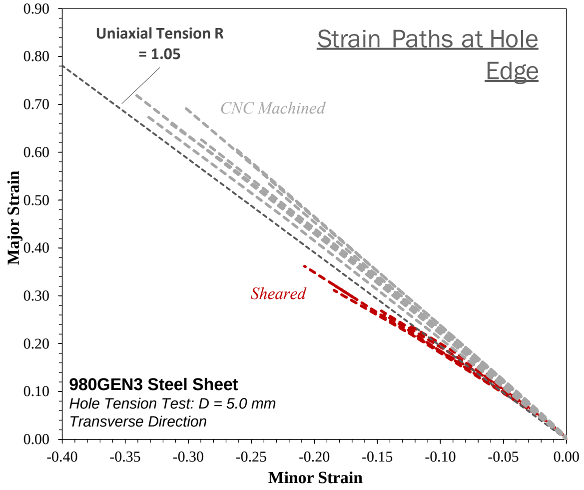


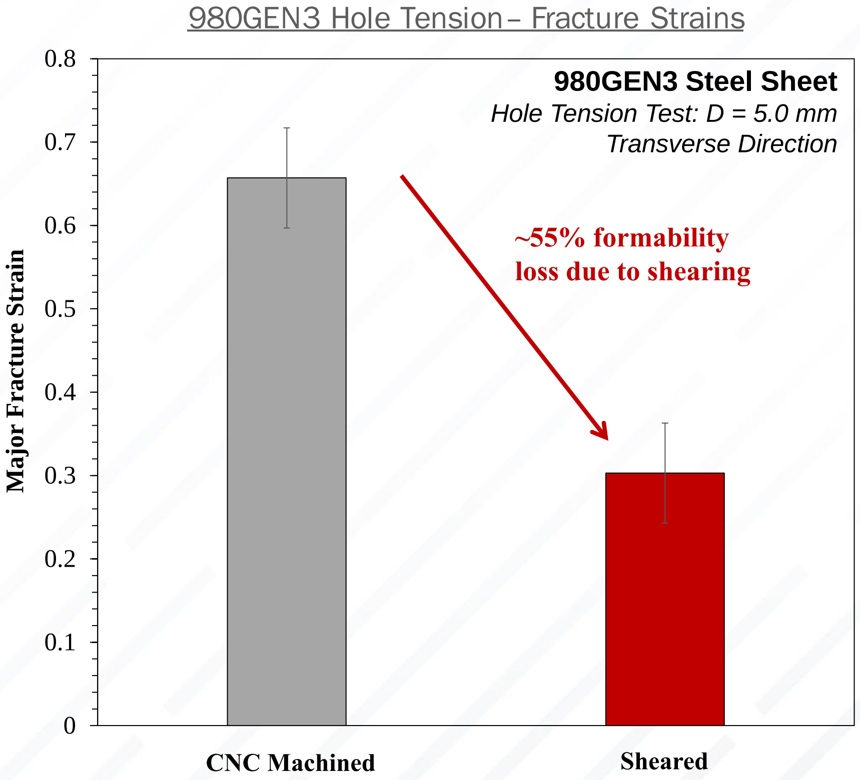
980GEN3 – CNC Machined Edge





980GEN3 – Sheared Edge (Burr Up)





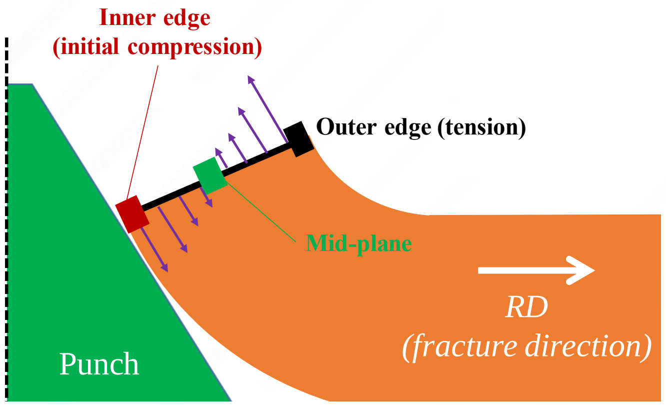
CONICAL HX FOR UNIAXIAL FRACTURE

Through-thickness stress gradient induced to suppress necking. Good for uniaxial fracture!

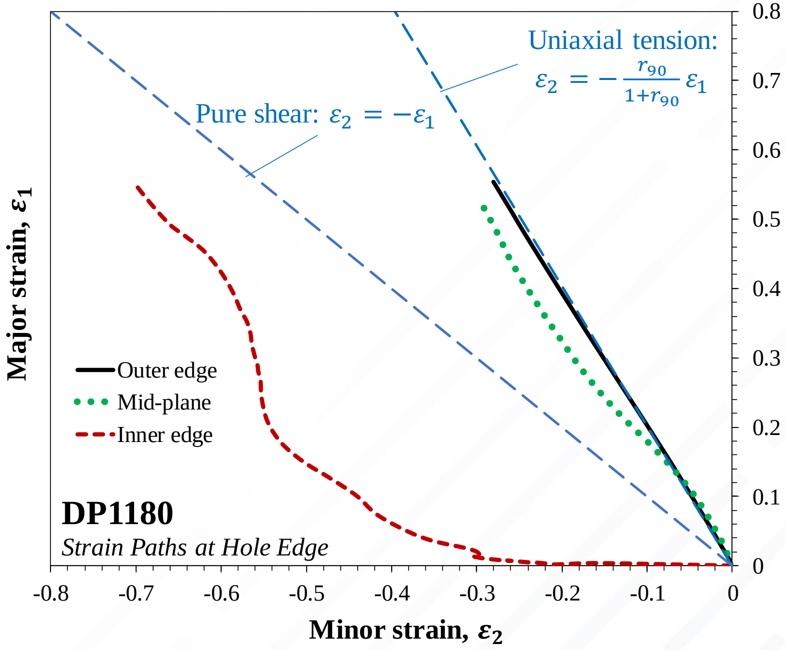
Cracks initiate at the outer edge under uniaxial tension. Can exploit outer hole diameter to estimate fracture strain.

Smaller initial hole diameter of 5.0 mm can promote higher fracture strains (Khameneh *et al.*, 2023).

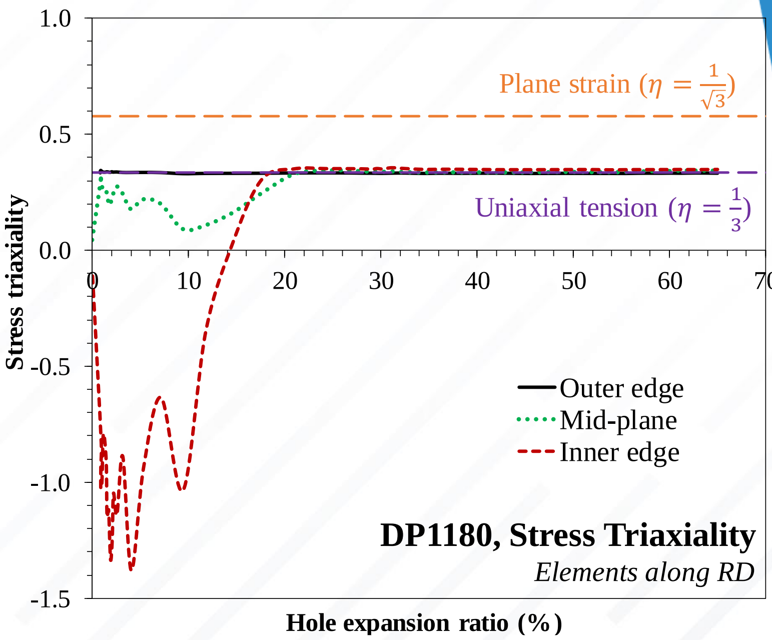
Through-thickness Gradients in Conical HX



Proportional Strain Path At Outer Edge



No Through-Thickness Necking



Narayanan, A., Abedini, A., Khameneh, F. and Butcher, C., 2023. An experimental methodology to characterize the uniaxial fracture strain of sheet metals using the conical hole expansion test. *Journal of Materials Engineering and Performance*, *32*(10), pp.4456-4482.
Khameneh, F., Abedini, A., Narayanan, A. and Butcher, C., 2023. On the Characterization of Fracture in Uniaxial Tension: Experiments and Modeling of DP1180 Steel Sheet. *Journal of Materials Engineering and Performance*, pp.1-32.

FRACTURE STRAINS FROM CONICAL HX (D=5.0 MM)

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Image processing software can be used to measure hole diameter at fracture. No need for DIC!

Can be employed to estimate fracture strains for both machined and sheared edge conditions.

Best-fit outer diameter can also be used to evaluate fracture if hole shape remains approximately circular at fracture.

Fracture strains for sheared edge lower by ~50% relative to machined condition.

Hole Expansion Fracture Metrics

➔ Hole expansion ratio:

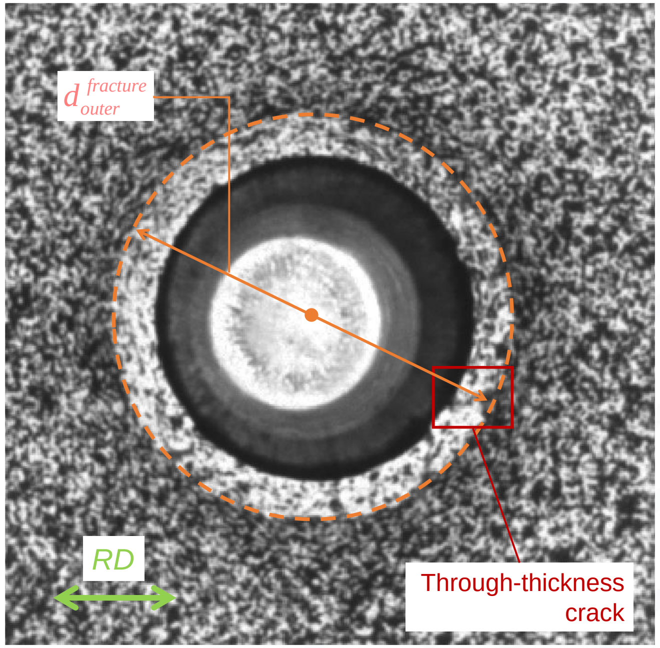
$$HER(\%) = \left(\frac{d_{inner}^{fracture} - d_{initial}}{d_{initial}} \right) \times 100$$

➔ Major fracture strain:

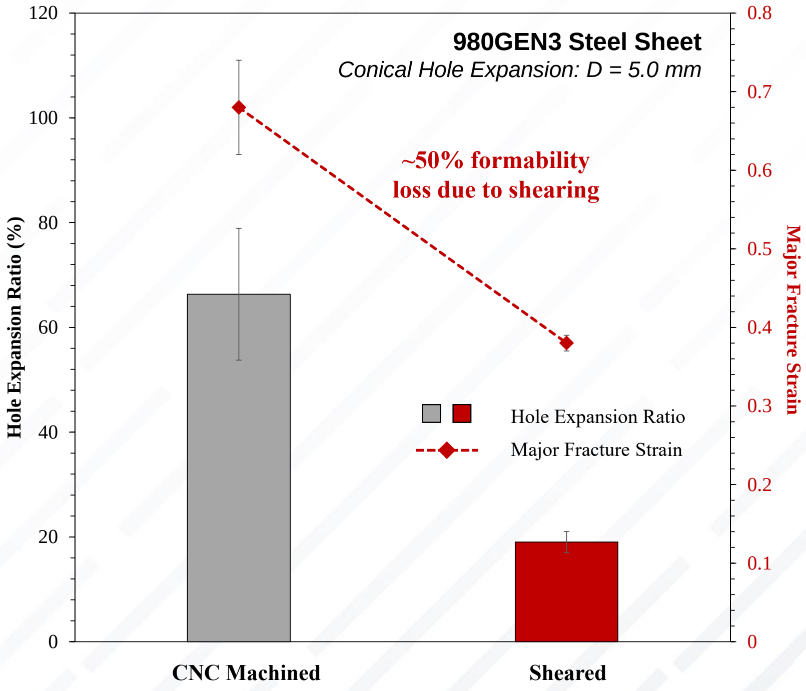
$$\varepsilon_1 = \ln\left(\frac{d_{outer}^{fracture}}{d_{initial}} \right)$$

➔ Initial Diameter: $d_{initial} = 5.0\,mm$

980GEN3 Conical HX – Sheared (Burr-up)



980GEN3 Conical HX – Fracture Strains



Narayanan, A., Abedini, A., Khameneh, F. and Butcher, C., 2023. An experimental methodology to characterize the uniaxial fracture strain of sheet metals using the conical hole expansion test. *Journal of Materials Engineering and Performance*, *32*(10), pp.4456-4482.

FLAT PUNCH HOLE EXPANSION TESTS (D=5.0 MM)

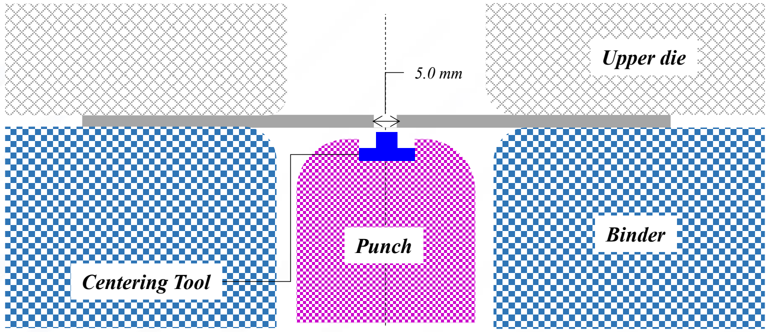
Plane stress deformation of the hole during flat punch HX. No through-thickness gradient to suppress necking.

Hole diameter influences strain gradients and failure location. Smaller hole size preferable for fracture.

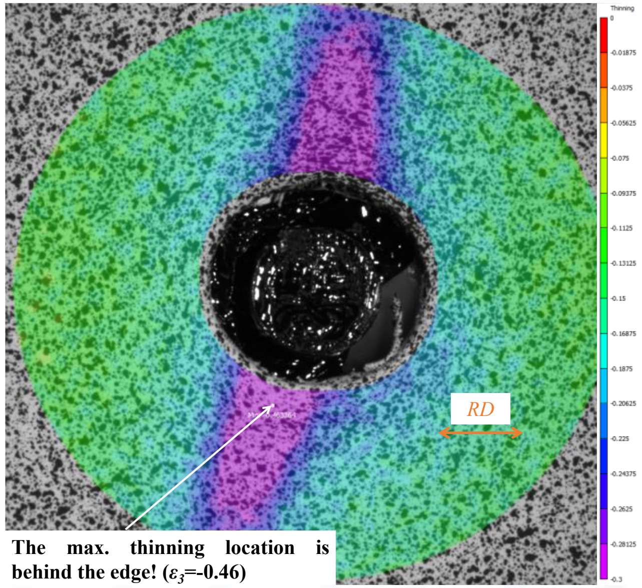
Localization and cracking expected away from CNC hole for 980GEN3!

Strain path at failure location is between uniaxial and plane strain. *Edge strains are conservative for fracture.*

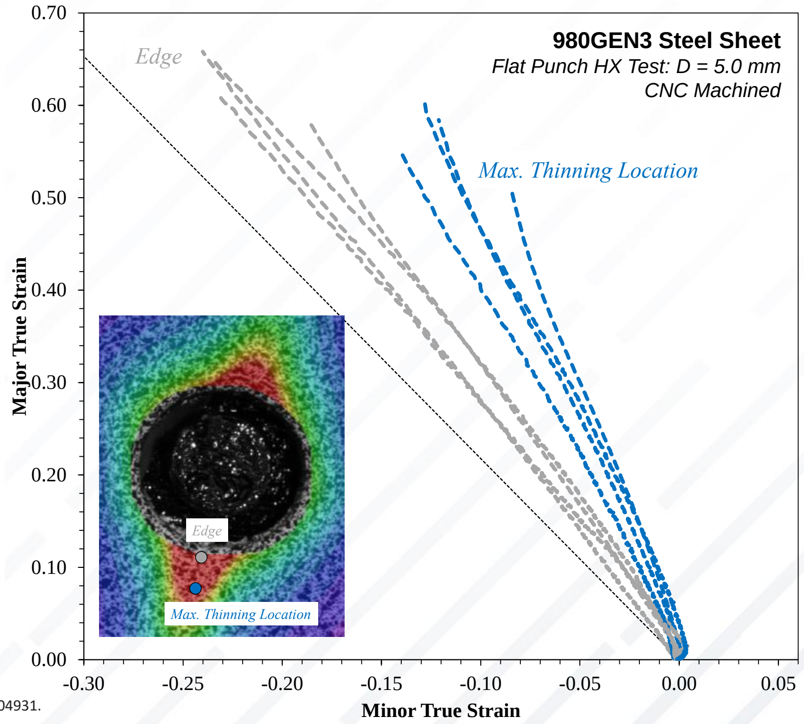
Schematic of Flat Punch HX



DIC ε_3 Contour: CNC Machined



Strain Paths During Flat Punch HX



Abedini, A., Narayanan, A. and Butcher, C., 2024. On the flat punch hole expansion test of sheet metals: Mechanics of deformation and evaluation of anisotropic plasticity models. *Mechanics of Materials*, *191*, p.104931.

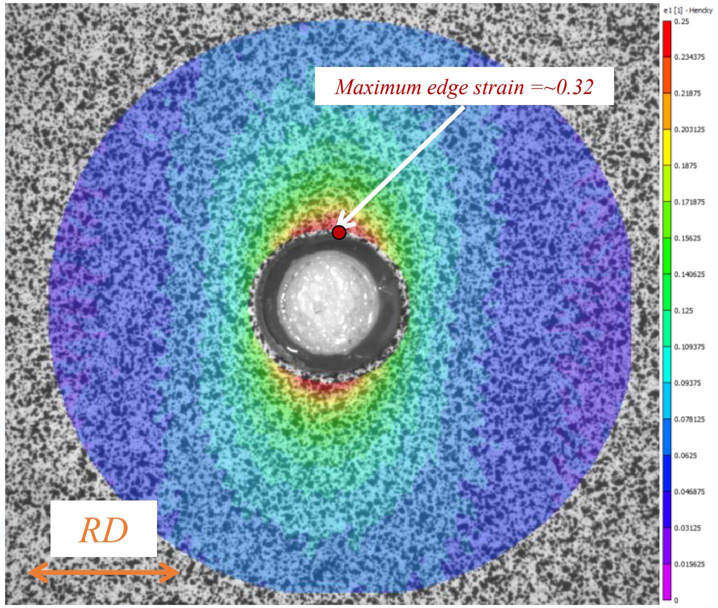
FLAT PUNCH HX: EDGE STRAINS AT FAILURE

Max. thinning occurs at the cut edge in the sheared flat punch HX test. Edge failure is expected.

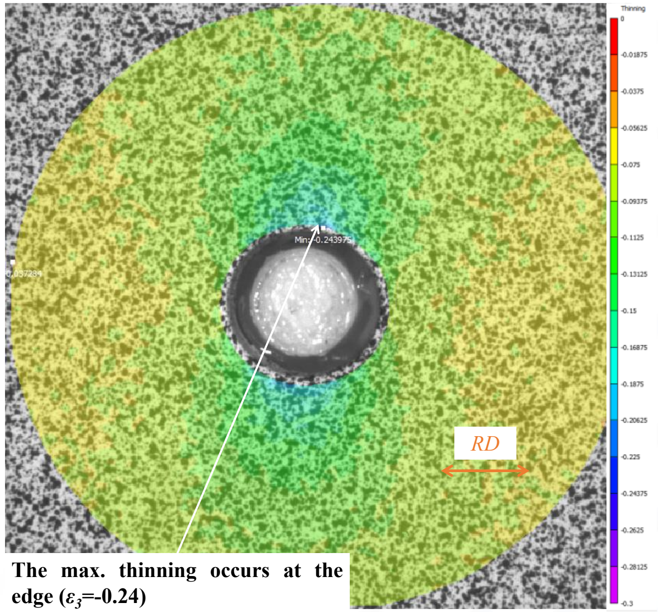
The fracture major strain for sheared edge is similar to other in-plane tests (~0.31).

The edge strains for machined hole are slightly lower than the tests that showed edge failure (0.65 vs 0.68).

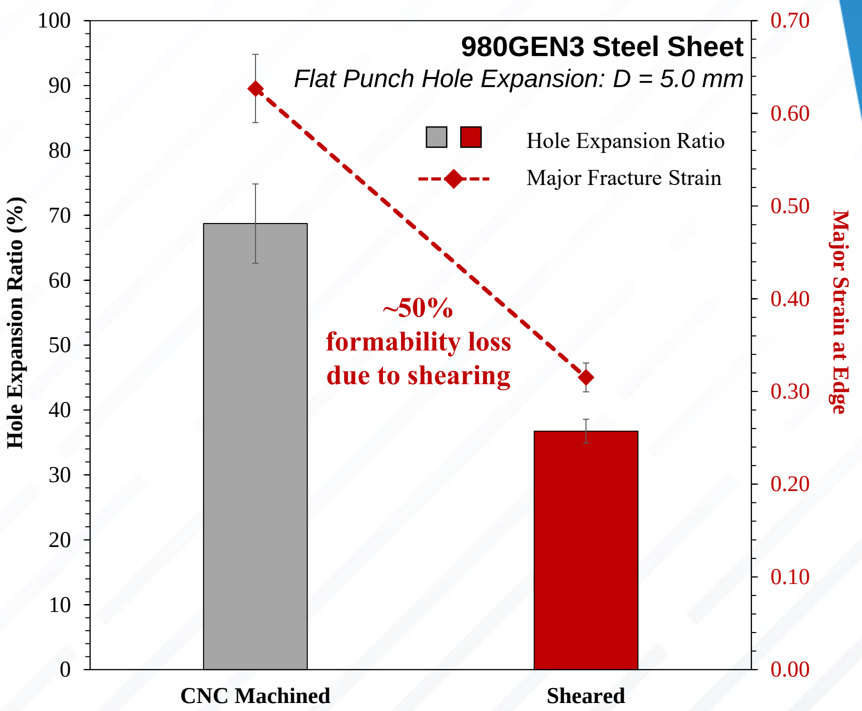
DIC ε_1 Contour: Sheared (Burr Up)



DIC ε_3 Contour: Sheared (Burr Up)



980GEN3 Flat Punch HX – Fracture Strains



FLAT PUNCH HX: FRACTURE STRAIN FROM HOLE SIZE MEASUREMENT

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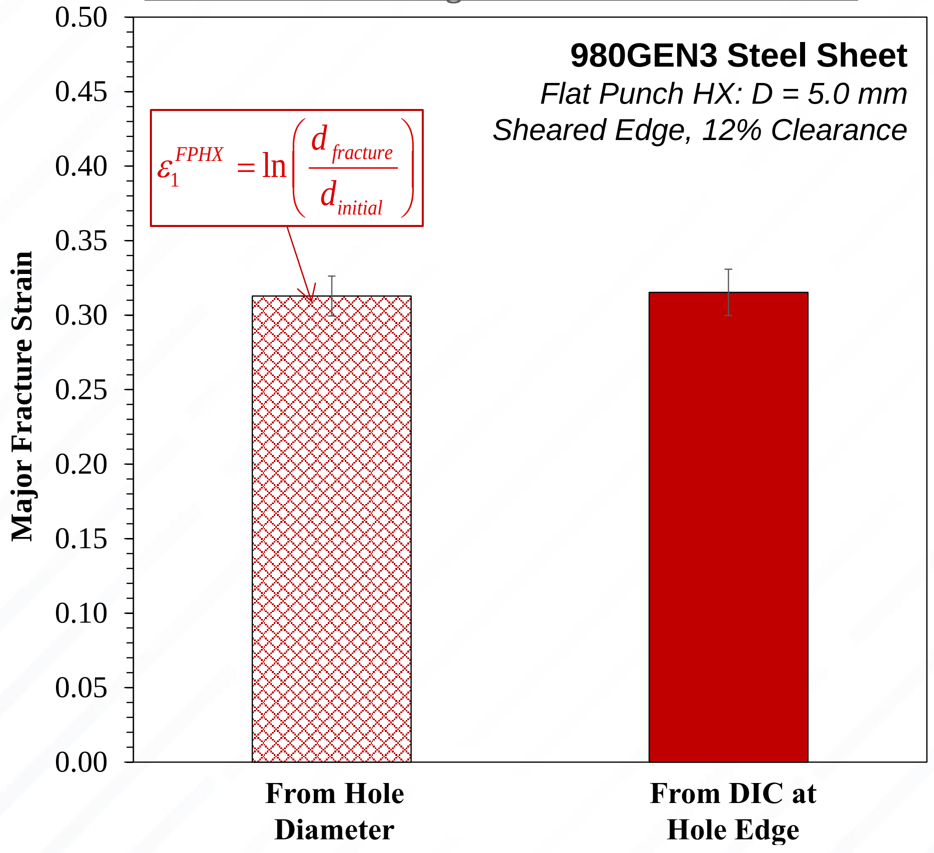
Fracture strain can be estimated using hole diameter if crack initiates from the hole edge like in conical HX.

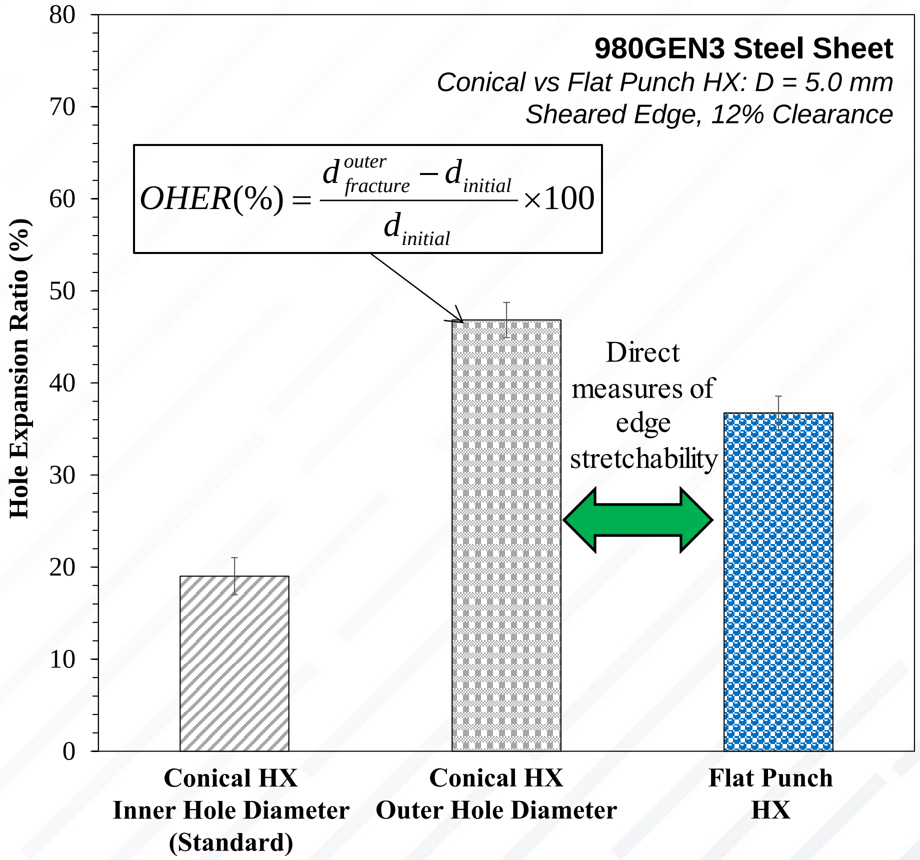
Measured strain using hole diameter in agreement with DIC local data for 980GEN3 sheared edge.

HER based on outer hole edge in conical HX may be better for comparing edge formability with other HX test types.

980GEN3 Sheared Edge – DIC vs Hole Measurement



980GEN3 – Hole Expansion Ratio Comparison



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EDGE FRACTURE TENSION TESTS (EFTT)

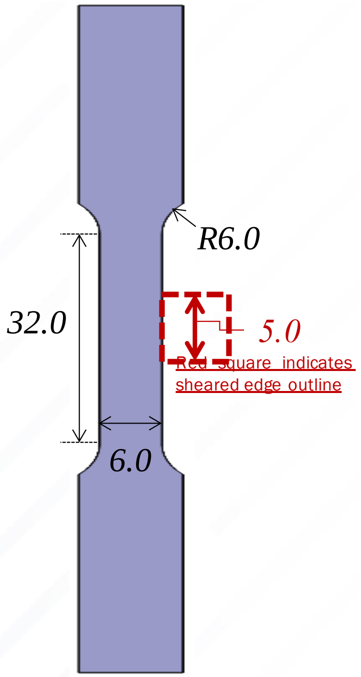
The sub-sized ASTM E8 geometry was chosen for edge fracture tensile tests.

Specimens for sheared edge testing were extracted from a 5.0 mm square shear cut hole.

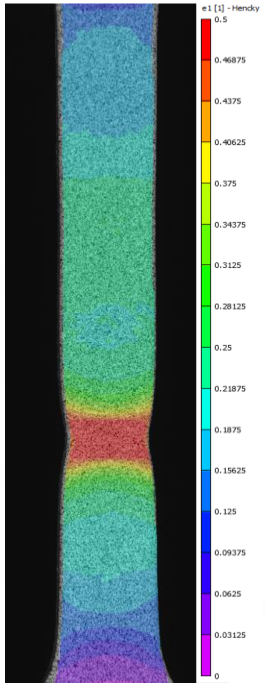
Occurrence of edge crack before onset of necking in 980GEN3 steel (mode II fracture).

Necking may precede edge crack in EFTT depending upon material (i.e. mode I or mode II+I type failures).

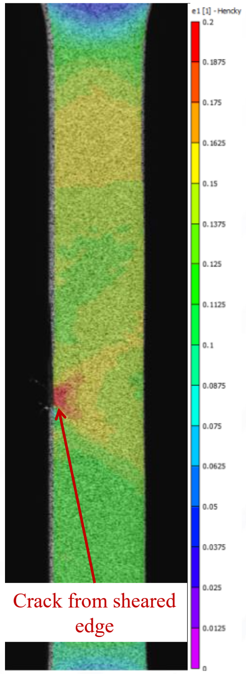
EFTT Geometry



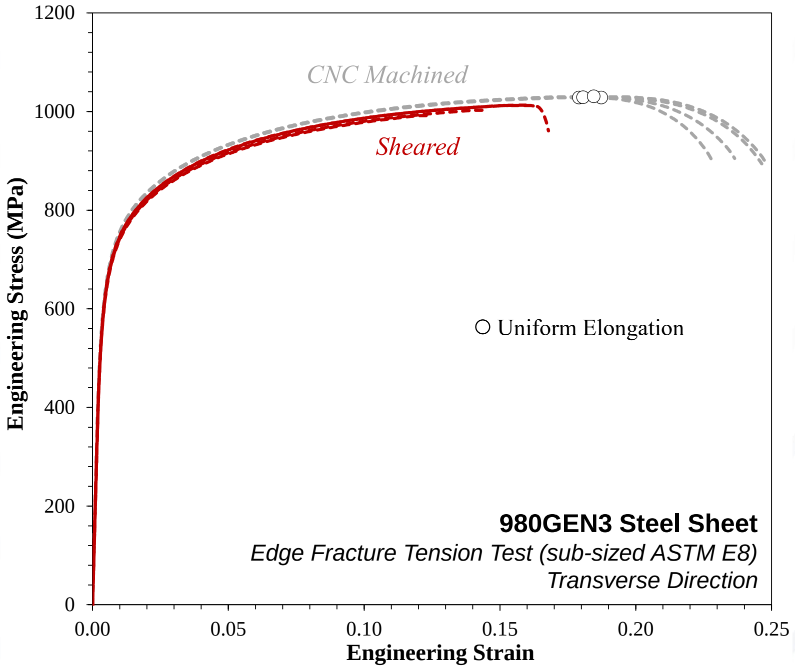
DIC Major Strain :CNC



DIC Major Strain: Sheared



Engineering Stress vs Strain Curves



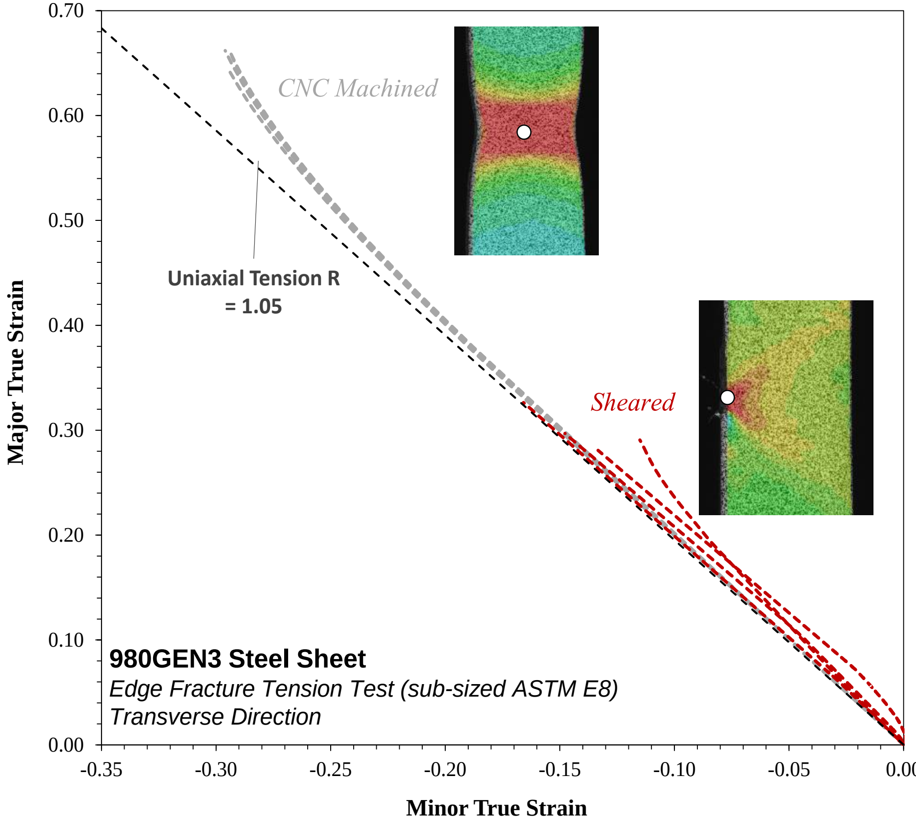
Golovashchenko, S.F. and Ilinich, A.M., 2005, January. Trimming of advanced high strength steels. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 42231, pp. 279-286).

EDGE FRACTURE TENSION: FRACTURE STRAINS

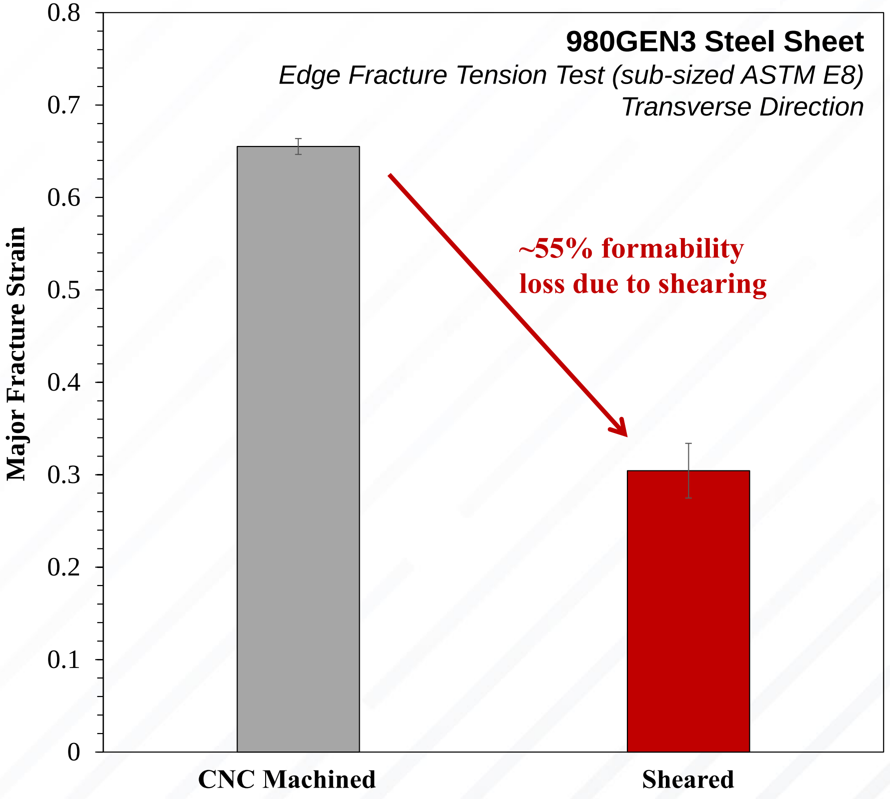
Non-linear strain path to fracture for machined EFTT due to diffuse and localized necking after UTS.

Strain drop of ~55% for sheared edge relative to machined condition. Trend similar to other test types…

Strain Path at Fracture Location



Fracture Strain Comparison



UNIAXIAL FRACTURE LIMITS FOR 980GEN3 STEEL

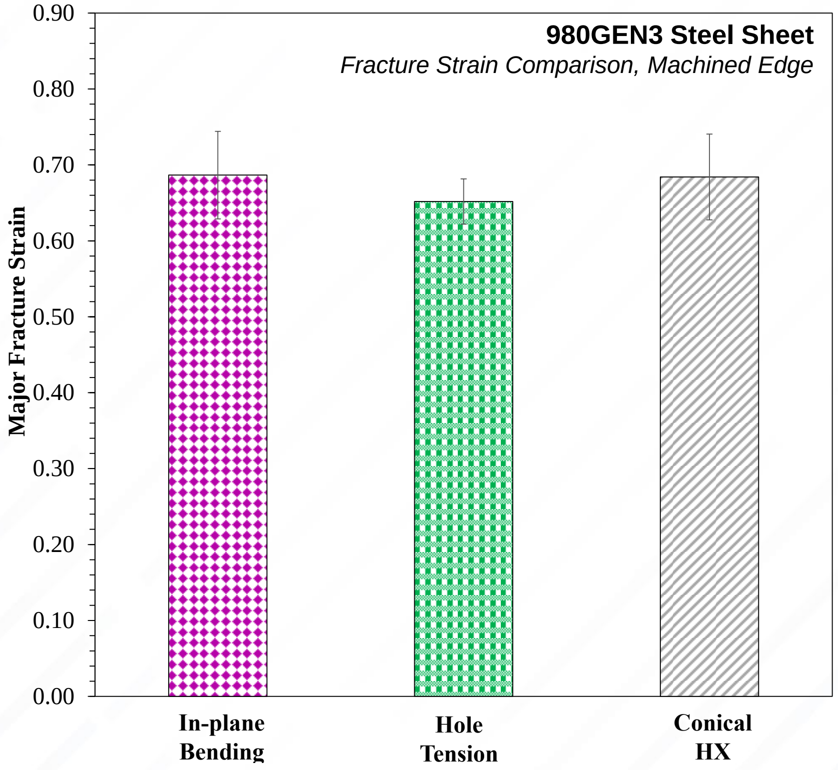
GDIS

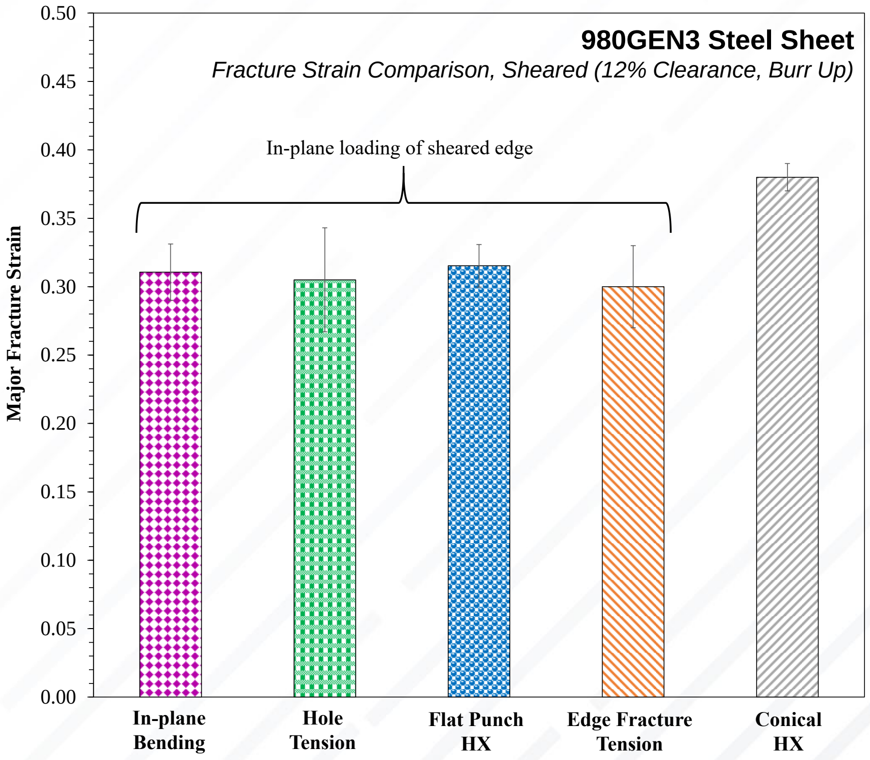
CNC strains comparable between tests for 980GEN3. Can be used for fracture model calibration of base metal.

Tensile and flat punch HX not considered due to necking and localization behind edge, respectively.

Similar sheared edge strains observed in 980GEN3 between tests that promote in-plane deformation (~0.31).

Conical HX exhibits higher sheared edge deformation than in-plane tests (0.38 vs 0.31).



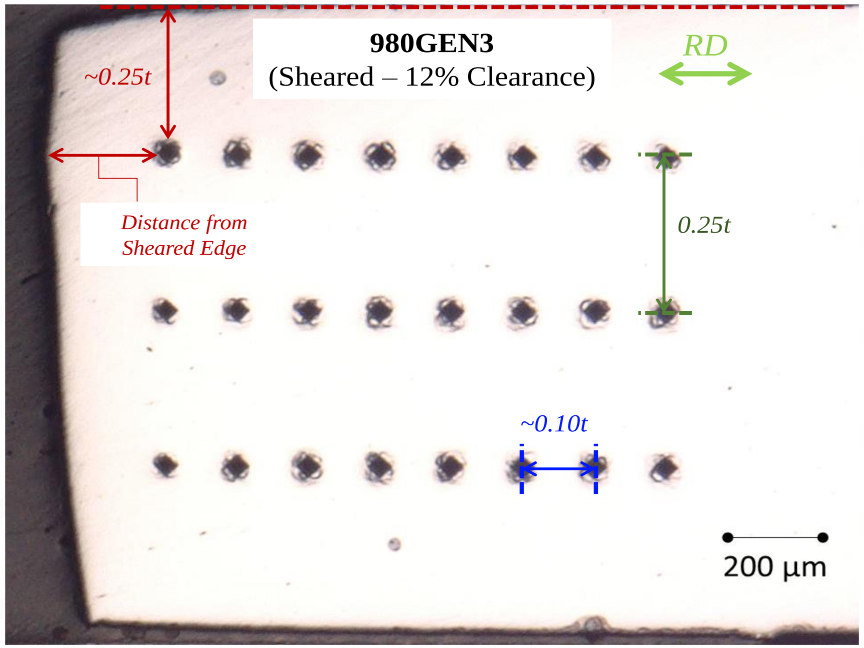


NEXT STEPS: SAZ STRAIN CHARACTERIZATION

➔ Boundary condition dependent fracture model for predicting sheared edge failure in FE models.

➔ Develop techniques to characterize strains within the SAZ for 980GEN3.

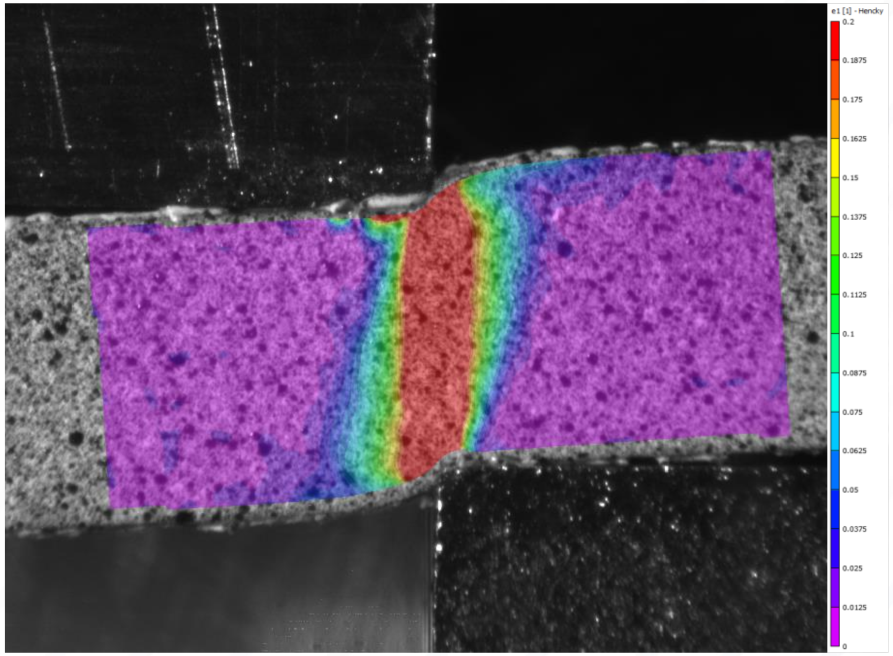
Hardness Mapping to Characterize SAZ



Compare Vickers Hardness

And DIC technique for SAZ strain measurement

DIC Strains of Through-Thickness Shear Cutting



➔ Integration and mapping of SAZ strains into simulations to predict edge splitting.

➔ Validation and evaluation of sheared edge FE models and lengthscale analysis.

SUMMARY & CONCLUSIONS

The in-plane bend test can be used for uniaxial fracture characterization to strains of ~0.70.

Relative change of the outer hole diameter can be utilized to determine conical HX strains.

980GEN3 fracture strains were independent of the boundary conditions for a machined edge.

980GEN3 cut edge is not as sensitive to applied loading as seen from various test methods.

Next phase of study will focus on edge fissure of hot rolled steels. *Strong boundary condition influence expected.*

FOR MORE INFORMATION

GDIS

Name: Advaith Narayanan

Company: University of Waterloo

Email: anadvait@uwaterloo.ca

Name: Cliff Butcher

Company: University of Waterloo

Email: cbutcher@uwaterloo.ca

Name: Jugraj Singh

Company: Stellantis

Email: jugraj.singh@stellantis.com

Name: Jonathan Smith

Company: Auto/Steel Partnership

Email: jsmith@a-sp.org

Name: Eric McCarty

Company: Auto/Steel Partnership

Email: emccarty@a-sp.org

Name: Dean Kanelos

Company: Nucor Corporation

Email: dean.kanelos@nucor.com